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AN ASSESSMENT OF THE RISK ARISING FROM ELECTRICAL EFFECTS ASSOCIATED WITH THE RELEASE OF CARBON FIBERS FROM GENERAL AVIATION AIRCRAFT FIRES

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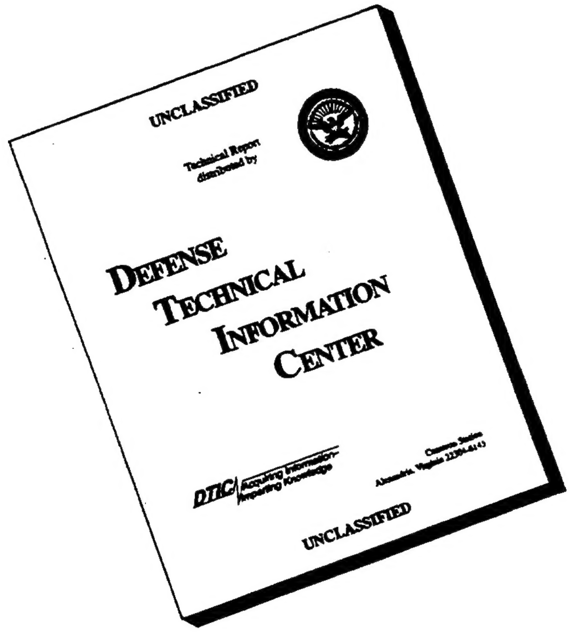

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PREFACE

The work presented in this report was conducted by Drs. Donald Rosenfield and Joseph Fiksel, under the direction of Dr. Ashok Kalelkar. The technical contributions of Dr. Wolf Elber and the guidance of both Dr. Elber and Mr. Robert Huston of the National Aeronautics and Space Administration are gratefully acknowledged.

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ABSTRACT

A risk assessment was conducted to estimate the potential economic losses through 1993 due to the electrical effects of carbon fibers released from U.S. general aviation aircraft. The usage of carbon fiber (CF) composites in aircraft structures is expected to increase substantially by 1993. Aircraft accidents often involve fires or explosions that could conceivably release minute carbon fibers, which might disperse in the atmosphere, penetrate buildings or enclosures, and cause damaging shorts to electronic equipment. Of an estimated 354 annual general aviation aircraft accidents with fire in the U.S. in 1993, approximately 88 could involve aircraft using carbon fibers. These accidents could result in the release of up to 1.1 kg. per accident, based on forecasts of CF usage through 1993 and experimental tests with burning CF composites.

A methodology was developed to compute estimated dollar losses by county and equipment type, using a Poisson model for the incidence of equipment failures. This approach incorporated data on the geographic distribution of potentially vulnerable facilities, as well as the mean CF exposure levels at which various equipment would fail. The results were then statistically aggregated to produce a national risk profile for estimated annual losses in 1993. The expected national loss was $253 per year (1977 dollars), and the likelihood of exceeding $107,000 in annual losses was estimated to be at most one in ten thousand. The sensitivity of these results to major input parameters was investigated, and it was found that under major parameter changes the expected losses would still remain low.

1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

Carbon fiber (CF) composites are being considered as an alternative material in the manufacture of private aircraft because of their light weight, high strength, and design flexibility. As their production costs decrease, CF composites are expected to find a considerable market in aircraft, aerospace, automotive, and industrial applications. However, in spite of the benefits of CF composites, a potential problem has been identified associated with the high conductivity of the carbon fibers. When composite structures are exposed to fire of sufficient duration and intensity, it is possible that the epoxy binding material will burn off, releasing individual fibers into the atmosphere. These fibers, if deposited on electronic equipment, could cause shorts in low-voltage circuits, resulting in damage to the equipment and possible economic losses for the facility or community involved. The National Aeronautics and Space Administration (NASA) has been charged with the task of investigating the risk to the United States as a whole from potential releases of CF in accidental aircraft fires. As a part of the program of risk assessment, Arthur D. Little, Inc., was contracted to quantify the risks associated with CF composite use in general aviation aircraft through the year 1993.

In order to perform the risk assessment, information was gleaned from several other agencies that are conducting parallel investigations, with NASA as the coordinating agency. The data incorporated into the analysis included fiber release characteristics for burning composites, vulnerability test results for various categories of equipment, and filter penetration experiments which are concerned with the ability of single fibers to enter buildings. However, uncertainties remain in data inputs for certain crucial elements of the risk analysis, which can introduce substantial uncertainty into the magnitude of the resulting risk estimates. Among the areas of greatest uncertainty are the frequency of fire incidents, the quantities of CF that are actually released,

and the equipment-disabling properties of fibers. In this report we have attempted to show uncertainties explicitly, to make conservative assumptions where necessary, and to determine the sensitivity of our risk estimates to these uncertainties and assumptions.

The objective of the present study was to assess the 1993 national risk of economic losses due to the utilization of carbon fiber composites in general aviation aircraft. In formulating this objective, we identified as sub-objectives the projection of potential usage of carbon fiber composites in U.S. general aviation aircraft through 1993, the development of an accident model for general aviation aircraft, the analysis of of the possible release amounts in general aviation accidents, the identification of demographic and industrial categories which might be exposed to such releases, and the assessment of the economic consequences of a given release. The demographic and economic analysis methods are modified versions of the approach used in a parallel study[1], in which we performed a similar risk analysis for commercial air carriers, using Monte Carlo simulation techniques to generate a national risk profile. In the course of the present study, a simplified methodology was developed for generating the national risk profile by direct computation. This is described in the next section.

1.2 METHODOLOGY

Risk assessment of carbon fiber releases resulting from general aviation accidents is different from previous risk assessment work regarding accidental CF releases from commercial aircraft in several ways. First, there are substantially more general aviation accidents per year than commercial aircraft accidents. This difference allows the utilization of analytic techniques based upon the statistics of large numbers. A second difference is that general aviation accidents are likely to occur in flight or near any of a large number of small airports, while commercial aircraft accidents generally occur near major metropolitan areas. Finally, the most significant difference lies in

the fact that general aviation fire accidents result in relatively small releases of carbon fiber (compared to possible releases in commercial aviation), and as a result the failure probabilities for equipment located near an accident are generally smaller than for commercial aviation.

Because of these differences an analytic model was used for the general aviation risk assessment instead of the Monte Carlo simulation procedure used for the commercial aviation analysis. The analytic model emphasizes the variation due to the random nature of failure events, rather than that due to physical conditions such as accident location and weather variations. Such a model is appropriate when the number of failures per release is low. In Appendix A it is shown that since each individual fiber or group of fibers has a small but finite probability of causing a failure, and since experiments have indicated that equipment failures obey an exponential probability law, then the details of the release conditions, with the exception of the total amount of fibers released, are relatively unimportant. As a result, given the amount released, each accidental release incident can be characterized by a Poisson probability distribution for the number of failures. This distribution can be successfully applied to events for which there are a large number of probabilistic trials with a low probability of occurrence in each trial.

A simulation approach to risk estimation would not be appropriate for several reasons. Since the dominant contribution to determining the number of failures is the probabilistic nature of the individual failures (i.e., the Poisson variation), the simulation approach requires a very large number of Monte Carlo trials in order to develop any confidence in the results. In addition, since general aviation accidents can occur in widely dispersed locations, a simulation would require a data collection effort that would be prohibitively costly.

The analytic methods that we have developed for the present application analyze the Poisson failure process for various equipment categories and utilize numerical calculations of probabilities to estimate risk. The analysis of equipment and facilities is performed on the county level, and the actual probability calculations are based on mixtures of Poisson distributions that apply for each combination of county, amount released and equipment category. Appendix A presents a detailed discussion of the Poisson process approach and the implications of low probability failures.

There were two key parameters within the analytic model which affected the number of failures per accident. The first was the amount of fibers released in an accident. By examining the different types of general aviation aircraft and their accident statistics, a distribution of amounts of carbon fibers potentially released in accidents was developed. The second key parameter was the density of facilities near the location of an accident. Thus, an important aspect of the accident model was a quantitative description of the distribution of facility densities. The 3,000 counties in the United States were chosen as a basis for estimating facility density, and hence a methodology was developed to apportion accidents to the various counties.

The overall approach consisted of the following steps, as illustrated in Figure 1-1:

- A distribution of possible CF release quantities was developed, based upon projected CF usage and several possible accident scenarios.

- For each accident scenario, the surface integral of exposure was estimated. This integral depends only on the quantity of fibers released and the fiber setting velocity.

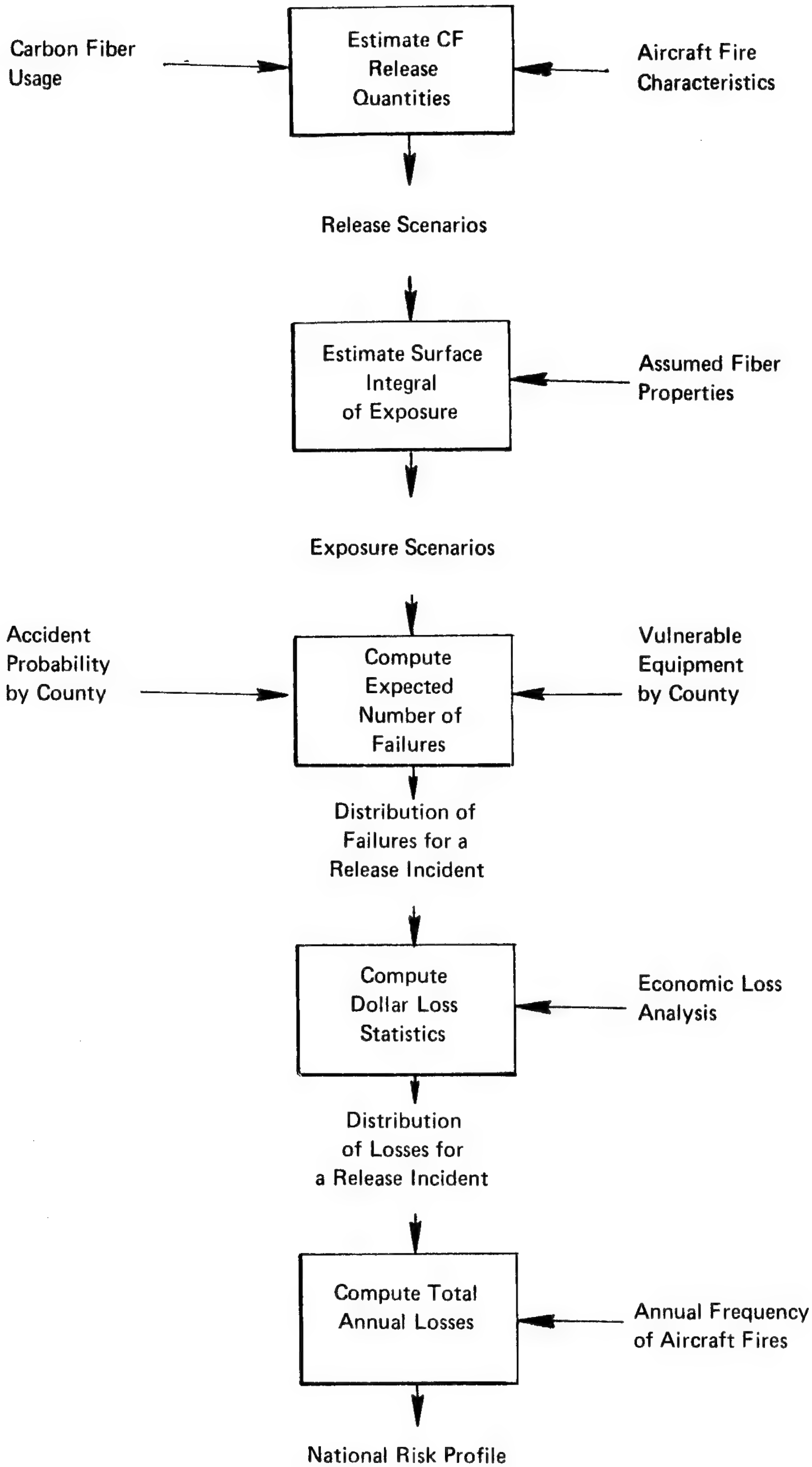


FIGURE 1–1 OVERVIEW OF METHODOLOGY

- The conditional probability of a random accidental fire occurring in each specific county was estimated as a function of local and itinerant general aviation operations.

- For each county in the U.S. the numbers of facilities in various industrial categories, as well as private residences and community services, were enumerated. Potentially vulnerable equipment was identified within each facility category.

- The expected number of failures for each class of equipment, county location, and release quantity were calculated, using information about equipment vulnerability in terms of exposure.

- Assuming that the number of failures was Poisson-distributed, a probability distribution was generated for the number of failures per release incident, aggregated over all counties and release scenarios.

- The proportion of failures occurring in each equipment category was estimated and economic losses were assessed, resulting in the statistics of dollar losses per release incident.

- Finally, the statistics of annual dollar losses were obtained using the estimated total number of fire incidents per year. On the basis of these statistics, a national risk profile was generated. The national risk profile is a graphical display of the probability of exceeding various levels of dollar loss as a result of the accidental release of CF in a general aviation fire.

Chapters 2 to 4 of this report present the various input data required for the risk analysis, and Chapter 5 describes the execution of the above methodology.

1.3 RISK ANALYSIS PRINCIPLES

The concept of risk can be defined as the potential for realization of unwanted negative consequences of an event or activity. In the case of this study, the unwanted negative consequences are the potential economic losses due to electronic equipment failure. The event or activity in question is the operation of general aviation aircraft utilizing carbon fiber composites. If risk is due to the presence of some causative agent, such as carbon fibers, then the degree of exposure* is measured by the amount of that agent which is potentially active.

In the past decade, an increasing amount of attention has been paid to problem areas involving activities with uncertain outcomes which might engender large risks. In order to deal with these problems the field of risk management has been created and developed. Risk management is a methodical scientific approach towards dealing with such risks. The quantitative aspects of risk management are often referred to as risk analysis. Examples of the application of this approach are in the areas of nuclear reactor safety and transportation of hazardous chemicals, such as liquefied natural gases.

The practice of risk management involves three basic steps: risk identification, risk measurement, and risk control. Potential risks can be identified through experience, judgment, or experimentation. In the case of the carbon fiber problem the nature of the risk is fairly well understood. The major challenge lies in risk measurement, that is, in determining the frequency of occurrence of events. Thus, the purpose of risk analysis is to create an analytic framework permitting measure-

*In this case, exposure is the time integral of concentration, with units of fiber-seconds per cubic meter.

ment of exposure and risk. Finally, if the measured risk is considered sufficiently great, control measures may be deemed necessary. Control measures would consist of any modifications to the mechanism of risk resulting in a reduction in the measured risk.

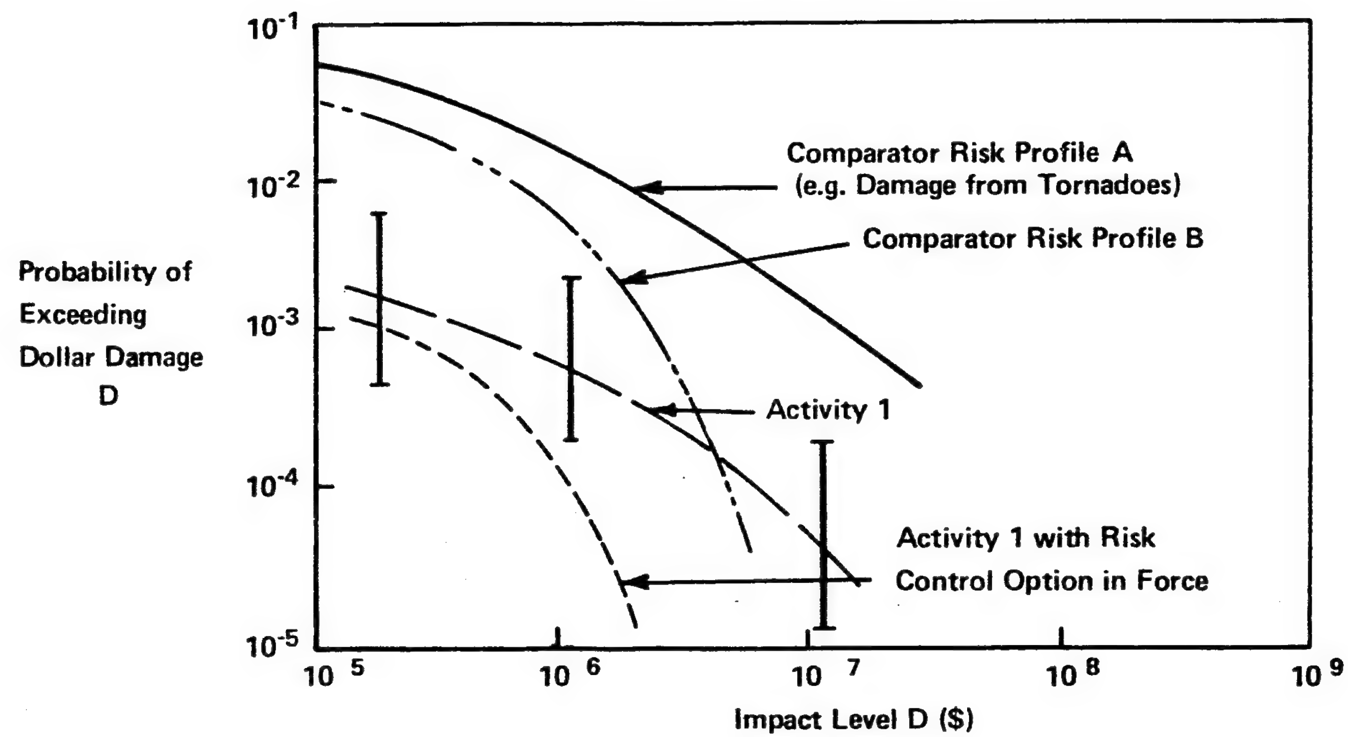
There are various possible representations which can be used to quantify risk. One possible representation is the expected value of losses over a given period of time. However, in order to deal with risks which may fluctuate over a wide range of losses and a correspondingly wide range of frequencies of occurrence, a preferred method of presentation is the risk profile. As discussed earlier, a risk profile is a graphical display of risk showing the probability distribution for exceeding various levels of unwanted impacts. A hypothetical example of a risk profile is shown in Figure 1-2. The activity in question is labeled Activity 1 and the risk profile for Activity 1 shows that economic impact can vary from $100,000 to $10 million with probabilities ranging from one in a thousand to one in ten thousand. This risk profile may be compared against other profiles for different types of events, such as the damage from tornadoes. In the diagram, two comparator risk profiles are shown. If risk control options are exercised, it may be possible to reduce the risk from Activity 1 as shown by the dotted curve at the bottom. The vertical lines are confidence bounds which show the uncertainty in the estimates of risk. Even though the actual risk may fall anywhere between these confidence bounds, the risk profile can still be used as an effective decision-making tool since it both quantifies in an absolute sense the risks imposed by Activity 1 and permits a comparison of these risks relative to other known risks.

1.4 REFERENCES

[1] Arthur D. Little, Inc., "An Assessment of the Risks Arising from Electrical Effects Associated with Carbon Fibers Released from Commercial Aviation Aircraft Fires". NASA Report No. NASA CR-159205 (February, 1980).

FIGURE 1-2

HYPOTHETICAL RISK PROFILE



2. CARBON FIBER USAGE FORECASTS

2.1 INTRODUCTION

Although carbon fiber (CF) composite materials are not presently being used in quantity in general aviation aircraft, there is considerable interest in the potential utilization of these materials for lightweight, high strength components.[1] The rate at which carbon fibers will be introduced in the general aviation industry is difficult to project due to the uncertainty of prices and design trends. There will generally be modest amounts of carbon fiber composites used on general aviation aircraft, particularly single reciprocating engine aircraft. Eventually there may be large amounts of carbon fiber composites on a few private aircraft. Lear Avia, for example, expects to be ultimately producing in small quantities a jet aircraft with almost 1,000 pounds of carbon fiber composites, although this projection did not directly affect our analysis.

In this section we present an overview of the projected usage of carbon fiber composites in general aviation, and then estimate the amount of CF in the 1993 fleet. These projections are based mainly on discussions between Arthur D. Little, Inc., aircraft manufacturers, and NASA, and represent only an approximate forecast.

2.2 OVERVIEW OF COMPOSITE USAGE

The general aviation and business aircraft industry, which includes both fixed wing and rotary aircraft, continues to represent a very small portion of fiber consumption within the aerospace industry. In 1978 this sector consumed no more than 3,000 kg. of carbon fibers which represented less than 4% of total aerospace usage. The major portion of this volume, probably as much as 65% to 70%, was used by rotary aircraft

[1]Larson, G.C., Composite Materials and General Aviation, Business and Commercial Aviation (September, 1979).

manufacturers, with the remainder split among eight North American fixed wing aircraft producers.

The rotary aircraft (helicopter) industry is made up of the following five companies: Sikorsky, Bell-Helicopter Textron, Boeing-Vertol, Hughes, and Kaman. The major output of these companies, currently estimated at 65% to 70%, goes into military service. The remainder is sold to various other customers in the commercial and general aviation market. All five companies are currently using carbon fiber to varying degrees, both in research, development, and evaluation programs sponsored by NASA or other government groups, and in selected operational applications.

The helicopter producers have generally made only limited inroads in the use of CF epoxy composites relative to the commercial and military fixed wing aircraft sectors, and in most cases on a retrofit basis. The primary reasons for this have been the limited number of units produced over which the development and production costs can be spread, and the general acceptability of considerably less expensive materials in most applications. It appears the contamination issue has not been a deterring factor in the use of CF. The primary application for CF has been as a stiffening agent in such areas as tail rotor spars, spar blades, main rotors, fairings, and horizontal stabilizers. In most cases where composite materials are utilized, fiber glass and/or Kevlar constitute the major portion of the fiber requirement with CF used in limited quantities for local stiffening. Normal ratios for glass and/or Kevlar versus graphite range between 5:1 to 10:1.

On a weight basis, total carbon fiber consumption within the helicopter industry in 1978 approached 7,000 kg. Only 2,000 of these kg. were believed to be used in areas other than military and commercial applications, with the military sector accounting for the lion's share. On a company-by-company basis, Sikorsky represented the largest consumer, utilizing about 4,000 of the total 7,000 kg. The vast majority of this

material, however, went into military aircraft with the S-76 "Spirit" being the sole general aviation aircraft to utilize CF. The next largest consumers were Boeing-Vertol and Kaman, each utilizing about 800 kg. of fiber. Here again the major portion went toward military applications. The remaining industry usage was split between Bell, Hughes and various subcontractors for the industry, such as Fiber Science.

The predominant application for CF to date has been in rotor and spar blades for the retrofit market. Uni-directional tape has been the predominant material form used. Some woven material is going into spar booms, but other than this, woven product usage is minimal. Current evaluation programs are under way at the various manufacturers for components such as rotor hubs, transmission shafts, gearbox struts, landing gear struts and various housings. It appears likely that uni-directional tape will be the predominant material used for these applications as well; however, woven material is expected to be used to at least some degree.

In terms of forecast carbon fiber consumption in non-military helicopter applications, we estimate usage will experience a steady climb up to a level of 12,000 to 15,000 kg. by 1985, which represents at least a six-fold increase over current levels. Probably as much as 30% of this usage will go into research and development and new component evaluation programs, with the remainder heavily weighted toward current applications. Uni-directional tape will continue to comprise the lion's share of the product form, with woven material gaining only slightly in popularity. It is difficult to predict usage levels after this period since any number of applications currently under evaluation might be specified during this period, any of which could greatly affect the total consumption levels. We feel, however, that fiber glass and Kevlar will continue to represent the major portion of composite material consumed and CF will continue to be used only in local stiffening applications in conjunction with the above materials.

With respect to the business and general aviation fixed wing aircraft industry, the primary manufacturers include Lear Avia, Beech, Gates

Learjet, Cessna, Grumman, Piper, and Rockwell International (all of the United States) and Canadair and deHavilland of Canada. Only a few of the above companies, namely Lear Avia, Beech, Cessna and Gates Learjet, are currently using carbon fiber, predominantly in evaluation programs. In addition to these aircraft manufacturers, there are a number of other small companies using limited amounts of carbon fiber in components made for both domestic and foreign aircraft producers.

As was the case in the helicopter industry, the use of CF has been considerably limited by low production volumes and the acceptability of more conventional and considerably less expensive materials. CF has usually only been specified as a local stiffening agent for components produced predominantly from fiber glass at Kevlar, the two largest of which are spoilers and flaps. Components produced entirely from fiber glass and/or Kevlar include such products as wing tips, wing/fuselage spars, radomes, engine cowlings, tail covers and various fairings.

The one major exception to the limited applicational usage for CF is Lear Avia, where they have been developing an all composite aircraft. This aircraft, labeled the Learfan, will be made entirely of carbon/epoxy and other composite materials with the exclusion of the engine, windows, and assorted other subcomponents. The total empty weight of this seven to eight passenger, turboprop aircraft will be 1,650 kg., 700 kg. of which will be comprised of composite materials.

The Learfan will use both pure fiber laminates as well as hybridized forms, including CF, glass and Kevlar. Possibly even boron will be used as well as phenolics and polymides where higher temperatures and/or stresses present a problem. Woven fabric is expected to comprise the majority of the material, although liberal amounts of uni-directional and multi-directional tape will also be employed.

This design is a radical deviation from the conventional applications of CF in strictly secondary structural components. Lear hopes to have this

aircraft test flown within one year and will then go into full production shortly afterwards, expecting to attain a production rate of 250 to 300 per year by 1983. While there is still a great deal of market speculation about its flight capabilities, potential CF contamination issues, and selling price (supposedly the Learfan will be priced at about $1.2 million), Lear states it already has orders for over 110 aircraft. The conductive filament problem has not been resolved to date and this might affect FAA certification. Because of the uncertainty concerning the Learfan and the limited amount of total composite weight involved, compared to the 1993 forecast, we did not consider its impact in the analysis.

Of the remaining business and general aviation aircraft producers, only Cessna and Beech appear to be using CF and only in extremely limited amounts. Cessna, with almost 50% of the general aviation aircraft market, is the only one of the two currently using CF in an operational application. The material is used as a stiffening agent in the spoilers and flaps of the new Citation III aircraft. Beech is still evaluating various components and to date has elected not to specify CF.

The current consumption level of carbon fiber by Lear Avia and the others was believed to be no higher than 1,000 kg. in 1978. Lear Avia alone accounted for well over 700 kg. of this. While it is uncertain at this time what kind of carbon fiber consumption levels will be attained at Lear Avia, depending upon the success of failure of the Learfan, it is highly unlikely that general consumption will increase very rapidly over the next five-year period. The primary reason for this pessimistic forecast is the high cost premiums associated with CF and the questionable need for such a high performance material in general aviation application. Even with a growth rate similar to that in rotary aircraft applications, carbon fiber usage within this sector, excluding Lear Avia, will be no larger than 1,500 to 2,000 kg. by 1985, which is insignificant relative to total consumption.

Lear Avia could greatly affect the consumption levels of this sector; however even with the most optimistic growth rates possible, total usage would still be small relative to commercial and military usage.

Lear Avia projects that by 1985 annual graphite fiber requirements could be in excess of 30,000 kg.

The overall future of graphite fiber within the general aviation sector therefore is not expected to be very promising. Current usage is limited, and even with significant increases in applications, because of the small production volume relative to the commercial and military sectors, this area will continue to account for less than 5% of total aerospace fiber consumption. We, nevertheless, have used conservatively high projections of 1993 carbon fiber usage, as described in Section 2.4 below.

2.3 GROWTH RATES FOR GENERAL AVIATION AIRCRAFT

For the purposes of this study, we have classified general aviation aircraft into three major categories:

1. Single reciprocating engine craft
2. Multi-engine and jet aircraft, and
3. Helicopters, non-fixed wing and non-powered aircraft

The identification of these three categories was based upon the accident analysis presented in Chapter 3, and upon size and structural differences between the different types of general aviation aircraft. Of the third category, helicopters represent the overwhelming majority of aircraft. The first two categories represent fixed wing powered aircraft. Of these type of aircraft, the first category represents larger aircraft and is expected to use larger amounts of carbon fiber composites in the future.

Historical growth rates for the different classes of aircraft are presented in Table 2-1. As noted, the growth rates for the three classes of aircraft are 4.8%, 6.3%, and 8.6% per year respectively. Since the three classes of aircraft are used to define accident categories, the three growth rates were applied in Chapter 3 to estimate the 1993 conditional probability that an accident involves an aircraft

TABLE 2-1

ACTIVE* GENERAL AVIATION AIRCRAFT

Year	-----Fixed Wing Aircraft------- Multi-Engine	Single-Engine	Rotor
1976	25,684	144,941	6408
1975	24,559	136,651	5200
1974	23,418	131,932	4224
1973	21,929	126,217	4213
1972	19,849	120,446	4100
1971	17,855	109,256	3916
Growth Rate (%/yr)	6.3%	4.8%	8.6%

*active aircraft is defined as one which has a current registration and was flown during the previous calendar year

Source: Aerospace Facts and Figures, 1978/79

of a given type. These growth rates also imply that the number of aircraft in use in 1993 will be 321,000, 72,500 and 25,000, respectively.

2.4 PROJECTED CF USAGE IN 1993

Any future projections of carbon fiber usage in general aviation aircraft are subject to some uncertainty. However, based on discussions with manufacturers it is anticipated that approximately 25% of the general aviation fleet will be using carbon fibers by 1993. This projection is based on the large increases in fleet size between now and 1993. A significant number of the newly constructed planes will be built with carbon fiber composites. Because of the uncertainty involved in these projections, our risk profiles were subjected to sensitivity analyses (see Chapter 6).

Based on these projections there will be 80,250 single reciprocating engine craft, 18,125 multi-engine and jet aircraft, and 6,250 helicopter and non-powered aircraft using carbon fibers in 1993. It is anticipated that there will be not more than 1.3 million kilograms of carbon fiber composites manufactured for use on general aviation aircraft by 1993. Using this conservative forecast, and based on the belief that there will be large amounts used on jet aircraft and still larger amounts on helicopters, we used the following projections for amount of composite per aircraft carrying CF in 1993.

Single reciprocating engines	7 kilograms
Multi-engine and Jet Aircraft	20.5 kilograms
Helicopter, non-fixed wing and non-powered	50.5 kilograms

These projections were used in Chapter 3 to determine the possible release amounts in general aviation accidents.

3. PROJECTION OF ACCIDENTAL CARBON FIBER RELEASES

3.1 INTRODUCTION

An important aspect of the risk assessment was a projection of the frequency and type of general aviation accidents that would result in accidental releases of carbon fibers. This involved an analysis of general aviation accident histories from NTSB data and characterization of the conditions associated with potential CF releases. Due to the complexity of the historical accident data, the analytical details are presented in Appendix B. This chapter discusses only the highlights of the analysis and presents the results that were subsequently used for risk estimation.

3.2 GENERAL AVIATION ACCIDENT CHARACTERISTICS

Three categories of general aviation aircraft were defined, as mentioned in Chapter 2. It was determined that accidents for these different aircraft types could be characterized to a sufficient extent by two key variables - the phase of operation and the level of damage sustained. Due to the Poisson methodology used in this risk assessment, weather conditions and precise accident locations were not significant in estimating the number of equipment failures per CF release incident.

The phase of operation was classified as either cruise or on or near airport, the latter classification encompassing takeoffs, landings, and static or taxi phases. The level of damage was classified as either substantial damage or total destruction, in accordance with NTSB designations. The conditional probability of having a specific aircraft type, phase, and damage level are shown in Table 3-1. These probabilities represent the fraction of incidents in which each combination of characteristics would occur. For example, given that an accident occurs, there is a one-third chance that it will involve total destruction of a single reciprocating engine craft during cruise. The figures in Table 3-1 are based on historical data and are adjusted to reflect the

TABLE 3-1

CONDITIONAL PROBABILITIES OF ACCIDENT CHARACTERISTICS IN 1993

	Cruise		On or Near Airport	
	Total Destruction	Substantial Damage	Total Destruction	Substantial Damage
Non-Fixed or Non-Powered	.072	.013	.043	.014
Single Reciprocating	.333	.023	.203	.034
Multiple or Jet	.101	.014	.122	.028

growth rates for each aircraft type through 1993, which were presented in Chapter 2.

To perform the national risk calculation, it was necessary to estimate the total number of general aviation accidents in the U.S. in 1993, and to allocate these accidents to different counties according to the degree of air traffic activity. The historical accident rate appeared to be relatively constant, and hence was projected to remain stable through 1993. Consequently, the annual number of general aviation accidents, including commuter and air taxi operations, was estimated at 354. Of these about 25%, or 88 accidents, would involve CF according to the usage projections in Chapter 2. These accidents were allocated to various counties based on the estimated number of local and itinerant operations in each county. The details of this procedure are presented in Appendix B.

3.3 PROJECTION OF AMOUNT RELEASED

Given that an accident occurs involving a general aviation aircraft using carbon fiber composites and that a subsequent fire results, a potential exists for release of carbon fibers. In order to estimate the resulting damage, it is necessary to know the potential exposure to the surrounding area due to carbon fibers. The phenomenon of carbon fiber release and dispersion involves a complex chain of events, and to physically model these events would require a knowledge of the fire parameters such as pool size, duration, and amount of fuel burned, as well as the weather conditions at the time of accident. Since these parameters would be difficult to specify in the case of randomly located general aviation accidents, we have adopted a simplified methodology (as described qualitatively in Chapter 1 and in detail in Appendix A) which circumvents the need for most information. The only information necessary is the total amount of carbon fibers released in the fire, since the distribution of the number of failed equipment becomes independent of the other release conditions. This section presents the assumptions concerning the amount of carbon fibers released in a general aviation fire accident, which depends on two factors:

- The amount of CF on the aircraft
- The severity of the fire and/or explosion

It was assumed that the amount released will be proportional to the total amount of carbon fiber composites being used on the aircraft. As noted in Chapter 2, there are three types of general aviation aircraft, namely single reciprocating engine planes, multiple and jet engine planes, and non-fixed wing and non-powered planes. The amounts of carbon fibers being used on these craft are presented in Chapter 2. It is forecasted that 25% of the 1993 fleet will be using carbon fibers and hence the probability that an accident will result in a CF release is 25%.

The model for general aviation aircraft accidents described in Section 3.2 defines severity in terms of the NTSB classification of substantial damage and total destruction. These classifications were used for the purposes of determining the percentage of fibers released in an accident. Based on experimental findings reported in the analysis of commercial aviation aircraft* it was estimated that not more than 1% of carbon fibers would be released in a fire and that not more than 2.5% would be released in most fire and explosion scenarios. In addition, in commercial aviation accidents not all of the carbon fiber composites would be consumed in a fire, while the explosive mode represents only a small minority of commercial aviation accidents.

Based on these considerations, we conservatively assumed that the carbon fiber released in a general aviation accident would be 2% and 0.5% of the total carbon fiber composite, respectively, for total destruction and substantial damage accidents. Since the carbon fiber mass comprises approximately 70% of the mass of the carbon fiber composite, these assumptions represent 2.9 and 0.7% of the carbon fiber mass respectively for total destruction and substantial damage accidents.

*See Reference 1, Chapter 1

From the assumptions in Chapter 2 about composite utilization in 1993, we determined the total mass of carbon fibers released for each combination of accident severity and aircraft type. These data are presented in Table 3-2. The maximum possible release is 1.09 kilograms for the case of a total destruction helicopter accident.

TABLE 3-2

MASS OF CARBON FIBERS RELEASED (KG.) FOR GENERAL AVIATION ACCIDENTS - 1993

	Substantial Damage Accident	Total Destruction Accident
Single Reciprocating Engine	.034	.14
Multiple or Jet Engine	.10	.41
Non-Fixed-Wing or Non-Powered	.27	1.09

4. DEMOGRAPHIC ANALYSIS OF VULNERABLE FACILITIES

4.1 INTRODUCTION

The national risk profile for economic losses resulting from accidental carbon fiber releases from general aviation aircraft was based on the distribution of facilities with vulnerable equipment. A set of parameters was selected to describe each U.S. county for the purposes of the risk analysis presented in Chapter 5. These parameters pertain to demographic data which are readily available from published sources. This chapter presents the basis for the demographic analysis, as well as the economic analysis of the consequences of failures. Most of the data utilized here were developed in a parallel study of air carrier fires and CF releases. (See Reference 1, Chapter 1).

4.2 METHODOLOGY

The first step in the analysis was to represent the facilities considered to be potentially vulnerable by demographic classes such as households or the Standard Industrial Classification (SIC) codes for businesses. For several other facility categories, indices were required where actual data on facilities were not available; for instance, population was used as a surrogate to measure the amount of police and fire protection services. Table 4-1 shows the facility categories and the demographic data used to represent each facility category. Table 4-2 shows the data sources for each of the demographic data classifications. The assignment of facility categories studied in the economic analysis to demographic data categories involved some aggregation. For example, the general manufacturing category includes equipment classes identified in specific manufacturing environments which were taken as representative of the level of vulnerable equipment in all manufacturing plants.

Given the data categories for facilities, the amount of activity in terms of number of pieces of equipment in each county was determined

TABLE 4-1

FACILITY AND DEMOGRAPHIC CATEGORIES

Facility Type	Demographic Data Category
Households	Families
Police Protection Services	Population
Fire Protection Services	Population
Post Office Sorting Centers	Population
Subways	Number of Rapid Transit Vehicles
Commuter and Intercity Railroad	Railroad Terminals
General Manufacturing	SIC Code 19
Manufacturers of Electronic Equipment	SIC Codes 3573, 3650, 3660, 3670
Telephone Company Switching Facilities	Families
Radio and Television Broadcasting	SIC Codes 4830, 4890
General Merchandise Retailers	SIC Codes 5310, 5600, 5700, 5900
Retail Grocers	SIC Code 5410
Financial and Insurance Services	SIC Codes 6020, 6100, 6200, 6300
Computer Services	SIC Code 7370
Electronic R&D Firms and Universities	SIC Codes 7391, 8220
Hospitals	Number of Hospital Beds
Airport Services	Number of Air Carrier Operations - 1977
Automobile and Truck Assembly	SIC Code 3710

TABLE 4-2

DEMOGRAPHIC DATA SOURCES

Demographic Data Category	Data Source
SIC Data	U.S. Census Bureau, 1976 County Business Patterns
Families, Population, Number of Hospital Beds	U.S. Census Bureau, 1977 County and City Data Book
Number of Rapid Transit Vehicles	American Public Transit Association
Railroad Terminals	The Official Railway Guide, North American Passenger Travel Edition, July/August 1979
Number of Air Carrier Operations - 1977	U.S. Department of Transportation, Federal Aviation Administration, Terminal Area Forecasts, Fiscal Years 1979-1990

from scaling factors. These scaling factors included such measures as the average number of employees per SIC category. For each facility surveyed in the economic analysis, the number of pieces of equipment and the value of the scaling factor for that facility were determined. From the survey, standard factors were developed, such as one piece of equipment class x for every 1,000 employees in SIC category y. In this manner, the number of pieces of equipment in each category of vulnerable equipment was determined for each facility category. Appendices C and D contain listings of the equipment categories, with the scaling factors used for each facility type.

For every facility and equipment combination, the following parameters were identified: the mean dosage for failure, the transfer functions for outside to inside CF exposure, and the dollar cost per failure. For convenience in the risk computation, described in detail in Chapter 5, the mean dosage for failure and the transfer functions were combined to develop the effective mean outside dosage $\bar{E}$ for failure. When there was a range of transfer functions depending on building characteristics, the arithmetic mean of the high and low transfer functions was used; this procedure resulted in a number of about the same order of magnitude as the high end of the transfer function range, which is a consistently conservative assumption. Equipment categories which had equivalent $\bar{E}$ values and equivalent demographic data categories were combined for efficiency in computer processing. The dollar cost per failure of one piece of equipment was derived as the weighted average of the unit costs for each equipment category.

Given the estimate of the number of pieces of equipment for each facility category and equipment type, the computer procedure described in Chapter 5 could be implemented, providing probabilities of equipment failure for each category. The risk profile for dollar losses was derived by combining these probabilities with the dollar loss per failure of equipment. These losses were taken as the sum of the equipment repair and facility disruption costs per failure of equipment. In theory, this procedure could overestimate losses if the expected number of pieces of equipment failing in a single facility were greater than one; in that

case the facility disruption cost, which might not increase beyond the first equipment failure, would be overestimated. However, with the CF releases being very low relative to the $\bar{E}$ values, the expected number of equipment failures in any facility would always be systematically lower than one. Appendix C shows the estimated dollar losses per equipment failure.

4.3 SUMMARY OF ECONOMIC ANALYSIS

Details of the economic loss analysis may be found in Reference 1, Chapter 1. Some of the major observations that resulted were as follows:

- Most industrial and commercial facilities are equipped for repair or replacement of electronic devices in the event of failures during normal operation.

- Equipment which are critical to the operation of a facility, such as computers, are usually given special protection, and backup procedures are often available to prevent facility shut-down.

- Much of the electronic equipment examined is virtually invulnerable to the expected levels of indoor. CF exposure (at most 10^6 fiber-seconds/m.^{3}) due to protective cabinets and filtration systems.

Consequently, there are few instances in which a facility would experience significant economic losses as a result of CF exposure. The maximum dollar loss estimated for a single equipment failure was the $65,800 attributed to the loss of a transformer substation switch. The generally low failure costs are reflected in the low risk estimates derived in Chapter 5.

5. DEVELOPMENT OF NATIONAL RISK PROFILE

5.1 INTRODUCTION

This chapter describes the methodology used to determine the national risk profile and presents an interpretation of the results. The methodology utilized a computer model to calculate the probability distribution for the consequences of a single accident. These single accident results were then extrapolated to obtain a national estimate of expected annual losses.

The remainder of the chapter is divided into four sections. Section 5.2 presents the methodology and results for the potential economic losses in a single automobile accident. The mathematical basis for the methodology in this section is presented in Appendices A and E. In Section 5.3, the results for a single incident are extrapolated to an annual risk profile. The extrapolation technique uses the distribution of dollar losses in a single accident to derive an annual dollar loss distribution based on an expected 88 accidents per year involving CF composites. In Section 5.4, results of a sensitivity analysis are presented. It is noted that the change in annual dollar loss probabilities with respect to the changes in input parameters, such as release amounts, can be represented by a very simple mathematical relationship. Finally Section 5.5 contains a summary discussion of the results.

Before examining the details of the methodology it is important to understand the principle of the Poisson approach. For a given release scenario and equipment type, the number of equipment failures may be approximated by a Poisson distribution. The mean number of failures is given by integrating the equipment density over the area in question and multiplying by the equipment failure probability, which is nearly linear in E for low values of the exposure E. Under modest assumptions, we can

aggregate over many release scenarios, and show that the average number of failures is proportional to the surface integral S of the exposure, which in turn may be shown to depend only on the amount released and the fiber settling velocity. Thus an expression is obtained for the mean number of failures per incident in terms of just the average facility density, the amount of CF released, and the equipment vulnerability. This enables us to assess the risk without requiring detailed data on accident conditions or geographic locations.

Most of the technical details of the methodology are presented in the appendices. There are, however, some fundamental mathematical relationships that control the results developed in this report. These relationships are presented below to emphasize their importance in the final analysis. A glossary of symbols used in the relationships discussed in this chapter is presented in Table 5-1.

The first key relationship is between λ, the expected number of equipment failures in an accident, and such parameters as the amount of carbon fibers released, the equipment vulnerability, and the density of facilities. For any given county and equipment class, the expected number of equipment failures per accident is proportional to the amount of carbon fibers released and the density of facilities, and is inversely proportional to the mean exposure to failure for the equipment. The actual computation of λ is done by summing up contributions from each county in the U.S. and from each equipment class. The mechanics of these computations and the determination of the probability distribution of the number of failures are presented in Appendix A.

The second set of relationships links the mean and standard deviation of the dollar loss in a single accident to the parameters of the distribution for the number of equipment failures in an accident. These relationships are based on standard formulae for conditional expectation, and they can be found, for example, in Parzen, E., Stochastic Processes, p. 55. The equations imply that the expected value of L, the total dollar

TABLE 5-1

GLOSSARY OF SYMBOLS

$\overline{E}$	=	Mean outside exposure to failure
N_o	=	Number of equipment failures in an accident
L	=	Total dollar loss in a single accident
X_o	=	Dollar loss resulting from a single equipment failure
λ_j	=	Expected number of equipments of type j that fail given an accident
$p(i)$	=	Probability that i pieces of equipment fail in an accident
$\overline{L}$	=	Total dollar loss annually for all accidents
M	=	Number of accidental failures involving CF nationally
λ	=	Expected value of N_o
E	=	Expectation
n	=	Dummy variable to denote number of events
X	=	Dummy variable for dollar loss
Var	=	Variance
$(X\|n)$	=	Variable X given dummy value n
Y	=	Dummy variable for dollar loss per accident

loss in a single accident, is proportional to λ, the expected number of equipment failures in an accident, and that the variance of L has two terms, one which is proportional to λ and one which is proportional to the variance of the number of failures per accident.

The final set of important relationships links the statistics of the total annual dollar loss for all accidents to the statistics of the dollar loss in a single accident. These results are based on the same type of conditional expectations relationships referred to above. The expected value of the annual dollar loss is proportional to the number of accidents per year and the expected value of the dollar loss per accident. The variance of the dollar loss per year is approximately proportional to the variance of the dollar loss per accident and the expected number of accidents per year.

To convert the statistics of annual dollar loss into a distribution, some standard statistical methods are used. The results obtained and the outcome of a sensitivity analysis, are presented in the remainder of the chapter.

5.2 COMPUTATION OF LOSSES PER INCIDENT

The computation of the dollar losses per automobile accident is performed in two separate steps. In the first step, a probability distribution of the number of failures contingent upon a single accident is calculated. In the second step, the statistics of the dollar losses (rather than the number of failures) are computed.

An analytic methodology was developed to compute the distribution of the number of failures contingent on a single fire accident. The methodology is based upon the fact that for a given county and equipment class, the number of failures is approximately Poisson distributed. This is due to the extremely low probability of equipment failure at the levels of exposure typically computed for automobile fires. Because the dominant variation in economic losses is due to the Poisson failure

process, this methodology does not require detailed modelling of release conditions or accident locations. As shown in Appendix A, the expected number of failures per accident is directly proportional to the geographic density of equipment and the amount of fibers released and inversely proportional to the equipment's mean failure level, $\bar{E}$.

Implementation of the Poisson methodology required tabulation of data for approximately 3,000 counties in the United States, 81 equipment categories, and several possible release amounts. To handle these data, a computer model was developed and used to determine the distribution of failures contingent upon a single fire incident. Figure 5-1 describes the logical flow of the model and its extrapolation to the national level. As explained in Appendix A, the model tabulates a mixture of a large number of Poisson random variables. There is a separate random variable for each combination of county, equipment category and amounts released. The model adds up the probabilities of any number of failures given each of these possible combinations and weighs them by the appropriate conditional probability of that scenario. The result is the probability that, given an accident in some county, a given number of failures will occur. This distribution is presented in Table 5-2.

The next step in the analysis was to develop the distribution of dollar loss given an accident. The mean and variance of the dollar losses per accident depend on the statistics of the number of failures and of the dollar loss per failure. For example, if there were five equipment failures, then the expected value of the dollar losses in the accident would be five times the expected value of the dollar loss per accident, and the variance would be five times the variance of the dollar loss per accident.

Formally, we used the computer-generated values of λ_j, the expected number of equipment of type j that failed given an accident. On an aggregate basis, the λ_j's represent failure rates for the given equip-

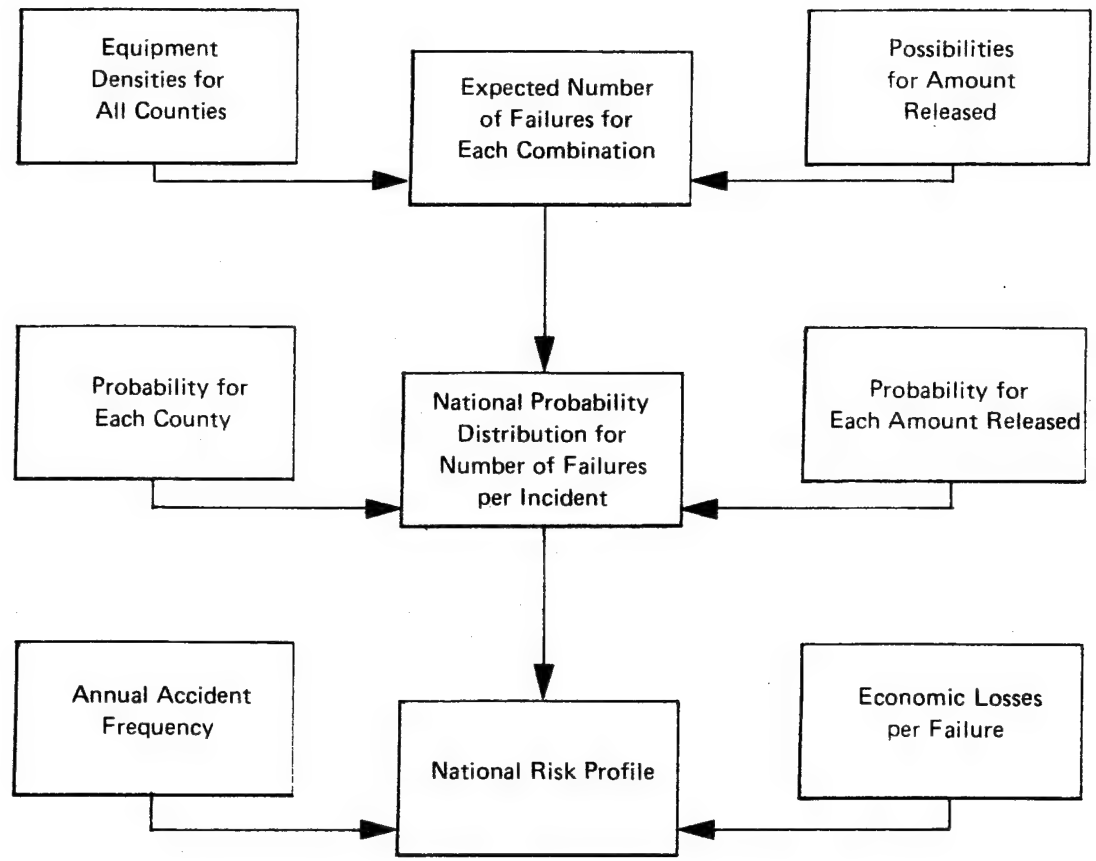


FIGURE 5-1: RISK ANALYSIS PROCEDURE

TABLE 5-2

PROBABILITY DISTRIBUTION OF NUMBER

OF FAILURES GIVEN AN ACCIDENT

Number of Failures	Probability
0	.98
1	1.8×10^{-2}
2	2×10^{-3}
3	2×10^{-4}
4	1×10^{-4}
5	4×10^{-5}
> 5	4×10^{-6}
Mean	0.022
Standard Deviaion	0.17

ment classes and the conditional probabilities that any given failure is of type j. Thus

$$\text{Prob(Equipment Type j Fails} | \text{Some Equipment Fails)} = \frac{\lambda_j}{\Sigma\lambda_j}$$

Using this probability function together with the economic loss estimate described in Chapter 4, we developed a distribution of the dollar loss per failure, X_0. We then used the following equations to find the mean and variance of L, the total loss per accident.

$$\begin{aligned} EL &= (EX_0)\ (EN) \\ \text{Var } L &\simeq (EN)\text{Var } X_0 + (EX_0)^2 \text{ Var } N \end{aligned} \qquad (5\text{-}1)$$

The expectation equation simply states that the expectation of total dollar loss in an accident is equal to the number of failures times the dollar loss per failure. There are two terms in the variance expression. The first term represents the variability due to the dollar loss per failure distribution, while the second term represents the variability in the number of failures per accident. The variance equation is not exact due to the correlation between the dollar loss per failure and the number of failures. The precise form of the computations is presented in Appendix E. Using those expressions, we derived estimates for the dollar losses in an accident, as presented in Table 5-3.

Although our methodology does not permit us to determine the precise distribution of dollar losses per accident, we developed upper bounds for these probabilities based on a standard result from probability theory. This result, which is known as the Chebyshev inequality, was used to determine upper bounds for the probability distribution of dollar losses per accident as well as upper bounds for the distribution of the dollar losses annually. The Chebyshev inequality (see, for example, Feller, Introduction to Probability Theory and Its Applications, Vol. II, p. 151) states that:

$$\text{Prob } (L \geq EL + t\sigma(L)) \leq 1/t^2$$

TABLE 5-3

STATISTICS OF ECONOMIC CONSEQUENCES FOR A SINGLE ACCIDENT (1993)

Variable Symbol	Variable Name	Expected Value	Standard Deviation
N_o	Number of equipment failures per incident	0.022	0.17
X_o	Dollar loss per failure	\$131	\$754
L	Total dollar loss per incident	\$2.88	\$114

Thus, the probability that the risk is more than 10 standard deviations above the mean is less than or equal to 10^{-2}. Utilizing the Chebyshev inequality, we developed Table 5-4* which presents upper bounds for risk values.

5.3 DERIVATION OF NATIONAL LOSS STATISTICS

The next step in the analysis was to compute the national risk profile, which requires only a knowledge of the mean and variance of dollar losses per accident. To derive the national risk profile, a two-step procedure was employed. These steps consisted of:

- Computation of the mean and the variance of the national risk profile, and
- Estimation of a probability distribution based on statistical results.

To compute the mean and variance of the national risk profile, the following conditional expectation equations were utilized:

$$E(\overline{L}) = (EM)\ EL$$

$$\mathrm{Var}(\overline{L}) = (EM)\ \mathrm{Var}\ L + (\mathrm{Var}\ M)\ (EL)^2$$

where

L = Dollar loss per accident
$\overline{L}$ = National dollar loss
M = Number of accidental fires with CF nationally
EM = Expected value of M
EL = Expected value of L

As noted in Chapter 3, there are 88 fire accidents annually involving general aviation aircraft using carbon fibers. Assuming that the number of accidents per year M is a Poisson random variable, then EM = 88, Var M = 88, and hence, $E\overline{L} = 253$ and $\sigma_{\overline{L}}$ = \$1,067. These statistics are summarized in Table 5-5. We again derived an upper bound for this distribution based

*A second version of the inequality used only for the first entry in Table 5-4, states that $\mathrm{Prob}(L \geq t\ EL) \leq 1/t$

TABLE 5-4

UPPER BOUNDS FOR THE PROBABILITY DISTRIBUTION OF DOLLAR LOSS PER ACCIDENT (1993)

Dollar Loss	Upper Bound for Probability that Loss Exceeds this Value Given that an Accident Occurs
$ 288	10^{-2}
11,403	10^{-4}
114,000	10^{-6}
1,140,000	10^{-8}

TABLE 5-5

STATISTICS OF ECONOMIC CONSEQUENCES FOR ALL ACCIDENTS NATIONALLY (1993)

Variable Symbol	Variable Name	Expected Value	Standard Deviation
L	Total dollar loss per incident	$2.88	$114
M	Number of incidents per year (Poisson Distribution)	88	88
$\overline{L}$	Total annual dollar loss	$253	$1,067

on the Chebyshev inequality. These results are presented in Table 5-6. The national risk profile is depicted graphically in Figure 5-2, incorporating the Chebyshev bounds for losses in excess of $50,000.

5.4 SENSITIVITY ANALYSIS

We next examined the sensitivity of the national risk profile to input assumptions. Some of these sensitivities could be hand calculated without any additional computer runs. The reason for this is that the number of failures per accident is a Poisson random variable. Hence the expected value and variance for the number of failures are approximately λ and from Equations (5-1), the expected loss per accident is:

$$\lambda \, E \, X_0$$

and the variance of loss per accident is approximately equal to

$$\lambda (E \, X_0{}^2 + \text{Var} \, X_0)$$

As an example of a sensitivity analysis using these equations, suppose that the CF amounts released in an accident decrease by a factor of 10. In this case the expected numbers of failures for the various equipment classes would all decrease by a factor of 10, while the conditional probability of dollar loss given a single failure would remain the same. As a result we can make the following calculations for the loss statistics. Note that the expected national loss has decreased by a factor of 10, to $25.

$$\begin{aligned} \lambda &= 0.0022 \\ EL &= 0.29 \\ \sigma_L &= 36 \\ E\overline{L} &= 25.3 \\ \sigma_{\overline{L}} &= 338 \end{aligned}$$

The Chebyshev inequality results are tabulated in Table 5-7.

We also examined the sensitivity for a highly conservative scenario (Table 5-8) in which amounts released were increased by a factor of ten.

TABLE 5-6

CHEBYSHEV BOUNDS FOR NATIONAL RISK PROFILE

Annual National Dollar Loss	Upper Bound for Probability that Loss Exceeds Value
10,923	10^{-2}
106,953	10^{-4}
1,067,253	10^{-6}

APPROXIMATE UPPER BOUND ON NATIONAL RISK PROFILE FOR GENERAL AVIATION ACCIDENTS (1993)

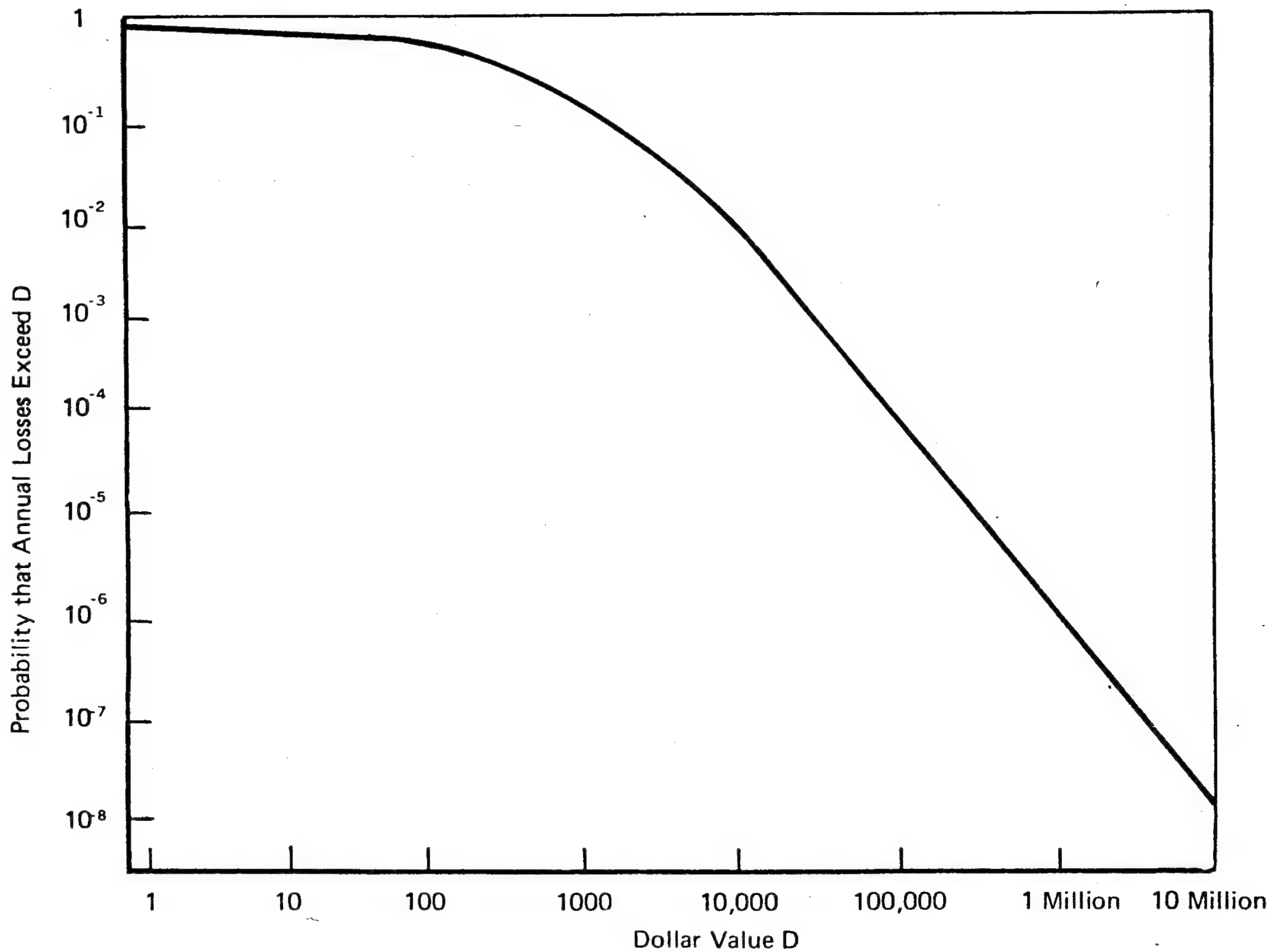


FIGURE 5-2

TABLE 5-7

CHEBYSHEV UPPER BOUNDS FOR SENSITIVITY ANALYSIS

WHERE RELEASE AMOUNTS DECREASE BY A FACTOR OF 10

Annual Dollar Loss for Nation (1993)	Upper Bound for Proability that Loss Exceeds Value
3,405	10^{-2}
33,825	10^{-4}
338,000	10^{-6}

TABLE 5-8

CHEBYSHEV UPPER BOUNDS FOR HIGHLY CONSERVATIVE SCENARIO

Annual Dollar Loss for Nation (1993)	Upper Bound for Probability that Loss Exceeds Value
106,953	10^{-3}
1,067,253	10^{-5}
10,670,253	10^{-7}

The same sensitivity analysis applies if the equipment $\overline{E}$ values decrease by a factor of ten. Note that the loss probabilities increase by a factor of 10 each for these cases. Thus, for example, the probability of exceeding a million dollar annual loss increases from approximately 10^{-6} to 10^{-5} In general, if the amount released increases by a given factor or if $\overline{E}$ values decrease by the same factor, then the probabilities will increase by that factor. In spite of the highly conservative assumption, the changed values in Table 5-8 still represent low probabilities of substantial losses.

5.5 SUMMARY OF RESULTS

The first step in the risk analysis number was to project the number of equipment failures, given that an accident occurred somewhere in the U.S. and released some quantity of carbon fibers. The expected number of failures per release incident was extremely small, resulting in an expected dollar loss per incident of only \$2.88, with a standard deviation of \$114. The probability of an accident resulting in losses exceeding \$11,400 was estimated to be at most one in ten thousand. Then based on an estimated 88 general aviation fire accidents per year, which could potentially release CF by 1993, it was found that the expected annual loss to the nation as a whole was \$253, with a standard deviation of \$1,067. The probability that the national loss will exceed \$107,000 was estimated to be at most one in ten thousand.

The sensitivity of these results to several input parameters was explored. The key parameter affecting the national risk is the amount of carbon fiber which could potentially be released in an accident. For example, decreasing the CF release quantities by a factor of 10 was found to decrease the national risk by about a factor of 10, to \$25. Conversely, increasing the CF released by a factor of 10 would increase the expected national risk to about \$2,530. The chances of the national losses exceeding \$1.07 million were estimated at one in one-hundred thousand for this scenario. Hence, this highly conservative scenario also results in low probabilities of substantial losses.

6. CONCLUSIONS

6.1 NATIONAL RISK

The results of the risk analysis indicate that the potential risks of economic losses due to CF releases from general aviation accidents are relatively small. The expected national risk was estimated to be only about $253 per year for 1993, with the average loss per incident being on the order of a few dollars. Furthermore, the chances of substantial losses are not significant. For example the probability of exceeding $11,000 loss in one year was estimated to be about 1/100. Although the possible consequences of a single accident can vary greatly, depending upon whether equipment failures do occur, the likelihood of such a failure is only 0.022 per incident.

It should be noted, however, that the risk estimates are subject to uncertainty from a number of different sources. The assumptions or uncertainties incorporated into the anlaysis are discussed below. Even when sensitivity analyses were performed to test the effect of these assumptions, the risks were found to be reasonably low. For example, the likelihood of exceeding $1 million due to CF releases from general aviation accidents is only 10^{-5} even if the amounts released are increased by a factor of 10.

6.2 SUMMARY OF UNCERTAINTIES

The uncertainties in the national risk estimate may be analyzed by considering the different data inputs incorporated into the model. The chief areas of uncertainty are the fraction of fibers released and the vulnerability levels of electronic equipment. However, even the most conservative scenarios in our sensitivity analyses indicate that the overall national risk is low. Some of the major areas of uncertainty are discussed below:

- Carbon fiber usage -- The projected usage could conceivably vary by a factor of 2 or 3 in terms of CF weight per air-

craft. However, such variations are taken into account in the sensitivity analysis by varying the amount of CF released given an accident.

- Number of fibers by weight -- The present report assumes that there are 5 x 10^9 single fibers per kilogram of CF available for release, based on previous NASA estimates. Although this value is subject to uncertainty, 5 x 10^9 represents a conservative estimate.

- Fraction of CF released -- Recent NASA test results indicate that the 2.9% figure used in our base analysis for total destruction accidents is extremely conservative, and that it is possible that no more than 0.1% of single fibers by weight would be released. In any case, the sensitivity analysis in which the amount of CF released increases by 10, covers the extreme case for this parameter.

- Accident probability -- The estimate of 340 accidents per year is based on nine years of historical data. A 98% Poisson upper confidence bound would increase this to only 377. Furthermore, although general aviation activity is increasing, there is no statistical evidence of an increase in the number of accidents occurring annually.

- Equipment vulnerability -- The estimated mean failure levels could vary considerably, but this possibility was addressed in the sensitivity analysis for the conservative scenario described in Chapter 5. The expected annual losses in this case, also assuming a ten-fold increase in CF release, were about $2500 for 1993.

- Economic losses -- The estimates of losses per equipment failure are subject to variations between facilities and regions, but this will contribute negligibly to the overall uncertainty.

In summary, the sensitivity analysis indicates that there is very little chance of substantial losses, with a "best estimate" expected annual loss for 1993 of $250. This level of risk is quite small compared to the direct property damage resulting annually from general aviation accidents. However, it should be noted that the present risk assessment has addressed only dollar losses due to equipment failure in the civilian sector, and does not quantify other categories of risk such as costs of protection or cleanup of equipment, CF releases from non-aviation sources such as incineration of sporting goods, possible environmental damage by carbon fibers, or impacts upon military operations.

APPENDIX A

METHODOLOGY AND SYSTEM OF EQUATIONS FOR GENERAL AVIATION RISK MODEL

A.1 INTRODUCTION

This appendix presents the methodology and procedure for constructing the risk profiles. The methodology applies the Poisson process to release types and is based on actual calculations of probabilities rather than a simulation. Section A.2 presents the rationale for the methodology and Section A.3 the procedure.

A.2 BACKGROUND

There were several characteristics that distinguished the general aviation analysis from the air carrier analysis also performed by Arthur D. Little. First, the collection of detailed locational data on accident scenarios (locations of accidents relative to locations of facilities) was not feasible. Second, the expected number of failed pieces of equipment per release was extremely small. Nearly all were substantially less than one.

Given these differences, a different type of methodology was used. The basis of the methodology is the computation of the expected number of failures given a release for a particular equipment type. The equation for this is:

$$N_o^r = \int_A n(dA)\left(1 - e^{-\frac{E(dA|r)}{E_o(dA)}}\right) \qquad (1)$$

where

r = Set of release conditions

N_o^r = Expected number of failures for given release

dA = Increment of surface area

A = Surface area

$n(dA)$ = Density of equipment within area increment dA

$E(dA|r)$ = Exposure within area increment dA given set of release conditions r

$E_o(dA)$ = Mean exposure to failure for equipment in given area dA (incorporating transfer functions)

For general aviation accidents, the amounts are very small and E tends to be a great deal smaller than E_o. For example, a typical exposure contour for a general aviation release showed maximum exposures of 10^3 $f.s/m^3$, while most E_o values are at least 10^7.

In view of this (1) can be approximated using Taylor series as:

$$N_o^r = \int_A n(dA) \left(\frac{E(dA|r)}{E_o(dA)} \right) \tag{2}$$

Although n(dA) may not be uniform, we can compute the average value of N_o (averaged over release conditions) for a given release amount of carbon fibers by

$$\overline{N}_o = \int_r f(r) \int_A n(dA) \frac{E(dA|r)}{E_o(dA)} dr = \frac{\overline{n}}{E_o} \int_r f(r) \int_A E(dA|r)dr \tag{3}$$

where

$\overline{N}_o$ = Expected number of failures averaged over all releases

r = Release conditions

$\frac{1}{E_0}$ = Reciprocal average exposure to failure of equipment in the county

$f(r)$ = Probability function for release conditions

and

$$\bar{n} = \frac{E_0 \int_r f(r) \int_A n\,(dA)\, \frac{E(dA|r)}{E_0(dA)}\, dr}{\int_r f(r) \int_A E(dA|r)\, dr} \tag{4}$$

In other words, $\bar{n}$ represents the average density of equipment where the averaging is over locations weighted by exposure and vulnerability values for the range of possible release conditions for a given amount released. Because of the random locations of accidents and random directions of wind, $\bar{n}$ can be approximated by D, the average density of equipment in the county. If it could be demonstrated that the largest concentrations of fibers generally occur at the locations of densest concentrations, then $\bar{n}$ would exceed D.

To investigate the possibility that $\bar{n} > D$, we looked at average city population densities weighted by population (i.e., the density of the city of the average person) and average county population densities weighted by population. Since the numbers were comparable, we concluded that average city density is approximately equal to average county density. By extending this relation, we assumed that the density at any accident location could be approximated by the city density and hence the county density. Therefore, as a first approximation, we assumed

$$D \simeq \bar{n} \tag{5}$$

We also note that for a given release amount, by integrating over the area of exposure

$$\int_A E(dA|r)\, dA = S$$

where S denotes the surface integral of exposure and is a constant.

That is, the surface integral of exposure is simply the number of fibers released times the settling velocity. Hence, no matter what the weather conditions are, all fibers contribute the same increments to the surface integral. Hence

$$\int_r f(r) \int_A E(dA|r) \quad dr = \int_r f(r)\, S\, dr = S \tag{6}$$

Combining (3), (5) and (6) the average number of failures for a given amount released is:

$$\overline{N}_o \simeq \frac{DS}{E_o} \tag{7}$$

This equation was one of the two key results of the analysis. The other key result was that the distribution of the number of failures is approximately Poisson with mean $\overline{N}_o$. Although this would follow directly if it could be assumed that the individual failures are negligibly correlated, this assumption did not appear to be immediately justifiable. The following represents an alternative approach to a justification for the Poisson distribution.

Consider the random variable for the number of failures given $\overline{N}_o$. In computing $\overline{N}_o$ there were two types of averaging performed. The first type was averaging the random failures given a release (i.e., the average in N_o^r). The second type was averaging over release conditions such as stability class, wind direction, etc.

Given the exponential failure law, then the number of failures given the average N_0^r is Poisson with mean equal to N_0^r and standard deviation equal to $\sqrt{N_0^r}$. The total variation, based on a formula for conditional expectation (See, for example, Parzen, Stochastic Processes, P. 55) is

$$\begin{aligned} \mathrm{Var}(\text{No. Failures}|\bar{N}_0) &= E(\mathrm{Var}\ \text{No. Failures}|N_0^r) \\ &+ \mathrm{Var}(E\ \text{Failures}|N_0^r) \\ &= EN_0^r + \mathrm{Var}\ N_0^r \end{aligned}$$

The first term EN_0^r is the Poisson variation. The second term is the variation due to release condition and density variations.

We performed some computations to assess the relative influence of each type of variation. Table A-1 presents examples of total deviations for various values of EN_0^r. It is assumed in the Table that Var N_0^r is four times EN_0^r, that is, the standard deviation due to release conditions and density variations is double the mean. This was simply an arbitrary but in our judgement conservative assumption made to test the importance of the Poisson variation. Column 1 is EN_0^r, Column 2 is the Poisson standard deviation which is equal to the standard deviation of the number of failures assuming a Poisson assumption is valid. That is, the second column is the square root of the first term of the right hand side of the above equation. Column 3 is the square root of the right hand side of the above equation.

The table shows that the assumption of a Poisson Process with parameter $\overline{N}_0$ has virtually the same variation as the actual process. Most of the actual expectations were substantially below the values in the table. The highest expectations were household goods for the New York City counties. For these cases, the densities were on the order of 56,000 per square mile and the E_0 value, incorporating average threshold values was 3.4×10^9. Thus, the maximum $\overline{N}_0$ for a helicopter total destruction release was

$$N_o = 56{,}000 \text{ mi}^{-2} \times \frac{1}{1609^2} \frac{\text{mi}^2}{\text{m}^2} \times 1.09 \text{ kg}$$

$$\times\ 10^9 \frac{\text{f}}{\text{kg}} \div .032 \frac{\text{m}}{\text{sec}} \div 3.4 \times 10^9 \frac{\text{f} \cdot \text{sec}}{\text{m}^2}$$

$$= .218$$

No other category except telephone exchanges and forklift equipment yields values that even come close to these household goods values. Furthermore, for the high density equipment categories, the densities and hence $\overline{N}_0$ will not show a great deal of variation with respect to release conditions.

The conclusion of this analysis is that the process can be approximated by a Poisson process with parameter N_0 as determined by Equation (7).

TABLE A-1

EXAMPLES OF VARIATION OF FAILURES

EXPECTATION EN_0^r	POISSON STANDARD DEVIATION	TOTAL DEVIATION
.25	.5	.7
.10	.32	.37
.05	.22	.23
.01	.1	.101
.005	.071	.071
.001	.032	.032

To account for different equipment types, it was noted that the number of total failures is the sum of individual Poisson processes.

A.3 POISSON MODEL

Let

$i = 1, \ldots, N$ be the counties

$j = 1, \ldots, M$ be the equipment SIC category combinations

$k = 1, \ldots, R$ be the cases of amount released

Let

$$\lambda_{ijk} = S_k D_{ij}/E_j \qquad (8)$$

where

S_k = Surface integral of exposure for release type k

D_{ij} = Density of equipment in county i

$\frac{1}{E_j}$ = Average reciprocal exposure to failure for equipment j incorporating transfer function (This was assumed to be independent of county).

The λ_{ijk} is the parameter of the Poisson Process for equipment type j, county i and release type k. Then for all equipment types, the parameters for the Poisson Process (which is the sum of individual Poisson Processes) is

$$\lambda_{ik} = \sum_j \lambda_{ijk} \qquad (9)$$

Then, for general aviation CF releases:

P_i = Prob(county i) - weighted factor of local and itinerant operations (see Appendix B)

Q_k = Prob(release k)

$$p(n) = \text{Prob}(n \text{ failures}) = \sum_{i,k} P_i Q_k e^{-\lambda_{ik}} \frac{(\lambda_{ik})^n}{n!} \qquad (10)$$

and the average failure rate is

$$\bar{\lambda} = \sum_{i,k} P_i Q_k \lambda_{ik} \qquad (11)$$

Because all of the λ values will be small, the calculations of the probabilities in (10) will be needed only for a limited set of values. In order to compute conditional risk profiles, probabilities of equipment types given a release needed to be computed. Bayes' theorem is utilized for this computation as follows. The prior probability of scenario k is

$$P_i Q_k$$

If n failures from a release are observed then the posterior probability of scenario k is

$$p(i,k|n) = \frac{p(n|i,k)p(i,k)}{\sum_{i,k} p(n|i,k)\, p(i,k)}$$

$$= \frac{P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^n / n!}{\sum_{i,k} P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^n / n!}$$

$$= \frac{P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^n}{\sum_{i,k} P_i Q_k e^{-\lambda_{ik}} (\lambda_{ik})^n}$$

Now given n failures from one release under scenario i, k, the probability of any one being type j is

$$p(j|n,i,k) = \frac{\lambda_{ijk}}{\lambda_{ik}}$$

Thus, given n failures from one release, the probability that the scenario is i, k, and the failure is type j is

$$P(j,i,k|n)$$

$$= p(j|n,i,k) \; p(i,k|n) = \frac{P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^n \; \dfrac{\lambda_{ijk}}{\lambda_{ik}}}{\Sigma P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^n} = \frac{P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^{n-1} \lambda_{ijk}}{\Sigma P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^n}$$

Thus,

$$p(j|n) = \sum_{i,k} p(j,ik|n)$$

$$= \frac{\sum_{i,k} P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^{n-1} \, \lambda_{ijk}}{\sum_{i,k} P_i Q_k \, e^{-\lambda_{ik}} (\lambda_{ik})^{n}} \tag{12}$$

For the case n = 1, it is seen that

$$p(j|1) \simeq \bar{p}_j = \frac{\lambda_j}{\bar{\lambda}} \tag{13}$$

where

$$\bar{\lambda}_j = \sum_{i,k} P_i Q_k \lambda_{ijk}$$

The computation of the risk profile is based on the expressions for $p(n)$ and $\bar{p}_j$. The $p(n)$ values were used by themselves to represent a risk profile for a single accident and were used to compute moments for numbers of failures. Due to equation (13) and the fact that multiple failures were unlikely $\bar{p}_j$ was used to compute aggregated cost moments rather than $p(j|n)$.

APPENDIX B: ANALYSIS OF GENERAL AVIATION ACCIDENTS

B.1 INTRODUCTION

In order to estimate the potential risks due to carbon fiber releases from general aviation accidents, it is necessary to quantify the probability of an accident in any given county. This chapter presents the model and the associated analysis for general aviation accidents. The model is based on accident and operation records compiled by the National Transportation Safety Board. It incorporates two probability factors: the probability of a general aviation fire accident and the conditional probability that the accident will be a given type. The type includes aircraft class, damage category, and whether the accident occurs during cruise or on or near the airport. Factors such as weather and proximity to airport are discussed but not utilized in the model. This appendix also includes a discussion of how the accident model is interfaced with the risk profile calculation. The profile is based on county data and thus requires the conditional probability that a given accident occurs in a given county.

B.2 DATA BASE AND IMPORTANT VARIABLES

The analysis of general aviation accidents was based on National Transportation Safety Board data tapes for nine years between 1968 and 1976. The tapes include accidents of U.S. and foreign-registered civil aircraft that occurred in the U.S., and contain over 400 items of information for each accident or incident. This includes detailed information about the accident conditions, the aircraft involved, the weather, the pilot, and the airport if the accident occurred in the proximity of one. In analyzing these tapes we focused upon accidents caused by fire or explosion and accidents in which fire or explosion occurred after impact. 3058 accidents of both types can be identified for the nine year period, and for each of these the following items of data were extracted for further consideration:

1. File number
2. Date of occurrence
3. Location
4. Type of aircraft
5. Number of engines
6. Type of power
7. Aircraft damage
8. Fire after impact
9. Type of accident
10. Phase of operation
11. Altitude of occurrence
12. Conditions of light
13. Type of weather
14. Airport proximity
15. Lateral distance from runway centerline
16. Terrain
17. Ceiling
18. Visibility
19. Precipitation
20. Location of fire
21. Fire damage

The objective in analyzing these data for the 3,058 fire accidents was to develop an expression of the form $P_t(X)$ that represents the probability of an accident of type t under conditions X. In examining a variable to determine its impact on the accident probability function, two criteria were applied. First, is the accident probability significantly influenced by the variable in a manner that can be utilized in a general aviation accident model? Second, does the variable affect carbon fiber dispersion?

In analyzing the data for the fire or explosion accidents for general aviation, we identifed the following variables that can affect accident probabilities or release condition.

1. Type of aircraft
2. Phase of operation
3. Level of damage
4. Weather
5. Location relative to airport

The types of aircraft are classified by number of engines, type of power and the existence of fixed or non-fixed wings. The number of accidents for each type is presented in Table B-1. In analyzing some of the other accident variables, it was noted that aircraft type affects

TABLE B-1

GENERAL AVIATION ACCIDENT TYPES INVOLVING FIRE (1968-1976)

General Type of Aircraft

Fixed Wing	2795
Helicopter	244
Glider	1
Balloon	15
Blimp	0
Dirigible	0
Rocket	0
Convertiplane	0
Gyroplane	3
Other	0

Number of Engines

0	15
1	2354
2	666
3	0
4	23

Type of Power

Reciprocating Engine	2912
Turbojet Engine	32
Turboprop Engine	51
Turbofan	3
None(Glider)	15
Turboshaft	45

variables such as extent of damage and phase of operation. In addition, the different types of general aviation aircraft may be utilizing different amounts of carbon fiber composite. The model consequently utilized three classes of general aviation aircraft and these are discussed in the next section.

The phase of operation affects carbon fiber release conditions and extent of damage three ways. First, fires may be more intense depending on the phase of operation. Take-off accidents, for example, would involve more fuel. Second, cruise accidents, because they take place off the ground, may result in releases with different dispersion characteristics. Third, accidents taking place on or near airports may take place in more densely settled areas than for cruise accidents. This, of course, greatly affects the economic impact of a release.

Because of the methodology utilized in analyzing the risk of carbon fiber usage in general aviation aircraft, the first two effects above of phase of operation are significant only to the extent that they affected the amount of carbon fiber released. The reason for this is that the surface integral method discussed in Section 1.2 requires only the amount of fibers released. The third effect above, due to density of facilities and population, is an important part of the model. The split of general aviation accidents between cruise and on-airport location was utilized to determine county locations of accidents.

The four phases of operation identified by NTSB include:

- Take off
- Landing
- Cruise
- Static or Taxi

The actual split utilized in the model is:

- Cruise
- On or near airport

NTSB recognizes several levels of damage in aircraft accidents and incidents. It is assumed that a carbon fiber release can occur only if the

level of damage is total destruction or substantial damage. For each level of damage a different amount of carbon fibers released was assumed.

Weather is an important variable in aircraft safety. In classifying weather conditions for accidents, NTSB recognizes the three different classifications.

- VFR - Visual Flight Rules
- IFR - Instrument Flight Rules
- Below Minimum

This classification appears to be a sufficent statistic for weather variables in terms of their effect on accident probabilities. For air carrier accidents it was noted that 49% of the relevant accidents occurred in IFR or below minimum conditions. The probability of IFR or below minimum weather at the major hub airports (weighted by operations) is only 11% and this indicates that the probability of accident per operation in IFR weather is substantially larger than for VFR weather. For general aviation accidents and incidents, the percentage of IFR and Below Minimum accidents is a great deal lower. Of the 3,058 accidents and incidents in the data base, only 16% of the non-static accidents occurred in IFR or below minimum weather. This may be due to the lower incidence of general aviation flights in IFR weather but in any case the percentage is a great deal closer to the national incidence of IFR weather than the percentage for air carrier accidents. We concluded that the weather variable need not play as important a role in a general aviation model.

The percentage of IFR and below minimum accidents was higher for larger general aviation aircraft (greater than one engine or non-reciprocating engine) and may also be correlated with the operational phase (cruise or on or near airport). However, the effect of the IFR probability at any airport is limited. For air carriers, even given the large increase in accident probabilities due to IFR weather, the weather factor does not create substantial adjustments in airport accident probabilities. Because weather does not have a substantial impact on general aviation accident statistics and because of the difficulty involved in making such adjustments, we did not incorporate weather into the general aviation accident model.

The final variable considered was accident location for those accidents occurring on or near airports. In NTSB reports, distance from the edge of the nearest runway and lateral distance from the runway were reported for accidents taking place off the airport. Distance from the edge of the runway was classified into 1/4 mile intervals up to 1 mile, 1 mile intervals up to 5 miles, and a single category for beyond 5 miles. In examining the distance distributions for different types of general aircraft phases and planes, there are three significantly different distance distributions. These distributions are for:

- Accidents during the take-off phase
- Accidents of single-engine planes during landing
- Accidents of other than single-engine planes during landing

However, the risk model for general aviation is not capable of utilizing the fine detail associated with the probabilistic distance distribution for accidents taking place near the airport. For this reason we did not utilize distance distributions within the accident model. Accidents are classified as taking place either during cruise or on or near airport.

It should also be noted that because of the large incidence of cruise accidents for general aviation, a third location variable, altitude was also considered. Table B-2 presents an altitude distribution for the accident and incident for which altitude was recorded. Although there are a substantial number of accidents taking place in the air, we again did not consider altitude because of the surface integration technique which considers only total amount released as a relevant variable.

B.3 ANALYSIS OF ACCIDENT VARIABLES

In view of the qualifications on location and weather noted in the previous section the only variables analyzed for the purposes of model development were:

- Type of aircraft
- Phase of operation
- Level of damage

TABLE B-2

ALTITUDE OF CRUISE ACCIDENTS AND INCIDENTS FOR GENERAL AVIATION AIRCRAFT (1968-1976)

Altitude of Occurrence (Feet)	Number of Accidents
0 - 500	58
500 - 1,000	41
1,000 - 2,000	36
2,000 - 5,000	75
5,000 - 10,000	55
10,000 - 20,000	20
20,000 - 30,000	2
30,000	1
On the Ground	974
Unknown	455
Total	1717

In addition to an analysis of these three variables in terms of accident frequencies, statistics have been compared for the beginning, the middle and end of the nine-year period to assess the possible existence of a time trend.

The data utilized in performing the analysis are presented in a series of tables that follow. The analysis also included some other data which were omitted from this report because the variables analyzed in these data are not ultimately utilized in the model. These variables include IFR-VFR weather frequencies and distance from the end of the runway for various phases of operation and aircraft type categories. Weather data are presented in aggregate for each subset of the overall data base, and the distance distribution for accidents taking place near the airport are presented for the overall data base. These data are presented for general reference and for corroboration of some of the conclusions presented in the previous section. For example, it is noted that the probability of IFR or below minimum is 16% but is somewhat higher for multiple engine and non-reciprocating craft. This, however, can be explained by the high incidence of on-airport accidents for these classifications, since on-airport accidents show a much higher percentage of IFR or below minimum accidents. Weather, however, is not judged to be a relevent variable for the purposes of analyzing risk. (It can also be noted that accidents taking place near airports comprise a distribution with most of its mass at small distances.)

Tables presented include the following:

Table B3 - Aggregate Data Base Statistics

Table B4 - Distance Statistics

Table B5 - Statistics for Fixed Wing Craft

TABLE B-3

AGGREGATE DATA BASE STATISTICS GENERAL AVIATION (1968-1976)

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	3058.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	359.	
TOTAL DESTRUCTION	2680.	
MINOR/NONE/UNKNOWN	19.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	48.	
NONSTATIC	3010.	
IFR		392.
VFR		2527.
BEL MIN/UNKNOWN/NOT REPORTED		91.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	622.	
SUBSTANTIAL DAMAGE		90.
TOTAL DESTRUCTION		531.
MINOR/NONE/UNKNOWN		1.
LANDING	638.	
SUBSTANTIAL DAMAGE		100.
TOTAL DESTRUCTION		533.
MINOR/NONE/UNKNOWN		5.
CRUISE	1717.	
SUBSTANTIAL DAMAGE		140.
TOTAL DESTRUCTION		1565.
MINOR/NONE/UNKNOWN		12.
STATIC/TAXI	58.	
SUBSTANTIAL DAMAGE		28.
TOTAL DESTRUCTION		29.
MINOR/NONE/UNKNOWN		1.
UNKNOWN	23.	
SUBSTANTIAL DAMAGE		1.
TOTAL DESTRUCTION		22.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	191.	
RESULT	2867.	

TABLE B-4

DISTANCE STATISTICS FOR GENERAL AVIATION FIRES

	Take-off	Landing
On Airport	209	257
On Seaplane Base	1	0
On Heliport	7	5
On Barge/Ship/Platform	0	0
In Traffic Pattern	148	143
Within 1/4 mile	83	24
Within 1/2 mile	38	24
Within 3/4 mile	13	8
Within 1 mile	25	22
Within 2 miles	16	22
Within 3 miles	2	17
Within 4 miles	4	15
Within 5 miles	2	9
Beyond 5 miles	58	84
Unknown/Not Reported	16	8

TABLE B-5

STATISTICS FOR FIXED WING CRAFT

TOTAL PLANE ACCIDENTS OR INCIDENTS 2795.
WITH FIRE INVOLVEMENT

LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	308.	
TOTAL DESTRUCTION	2468.	
MINOR/NONE/UNKNOWN	19.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	37.	
NONSTATIC	2758.	
IFR		385.
VFR		2287.
BEL MIN/UNKNOWN/NOT REPORTED		86.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	584.	
SUBSTANTIAL DAMAGE		78.
TOTAL DESTRUCTION		505.
MINOR/NONE/UNKNOWN		1.
LANDING	589.	
SUBSTANTIAL DAMAGE		90.
TOTAL DESTRUCTION		494.
MINOR/NONE/UNKNOWN		5.
CRUISE	1561.	
SUBSTANTIAL DAMAGE		116.
TOTAL DESTRUCTION		1433.
MINOR/NONE/UNKNOWN		12.
STATIC/TAXI	41.	
SUBSTANTIAL DAMAGE		23.
TOTAL DESTRUCTION		17.
MINOR/NONE/UNKNOWN		1.
UNKNOWN	20.	
SUBSTANTIAL DAMAGE		1.
TOTAL DESTRUCTION		19.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	175.	
RESULT	2620.	

TABLE B-6

STATISTICS FOR NON-FIXED WING CRAFT

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	263.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	51.	
TOTAL DESTRUCTION	212.	
MINOR/NONE/UNKNOWN	0.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	11.	
NONSTATIC	252.	
IFR		7.
VFR		240.
BEL MIN/UNKNOWN/NOT REPORTED		5.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	38.	
SUBSTANTIAL DAMAGE		12.
TOTAL DESTRUCTION		26.
MINOR/NONE/UNKNOWN		0.
LANDING	49.	
SUBSTANTIAL DAMAGE		10.
TOTAL DESTRUCTION		39.
MINOR/NONE/UNKNOWN		0.
CRUISE	156.	
SUBSTANTIAL DAMAGE		24.
TOTAL DESTRUCTION		132.
MINOR/NONE/UNKNOWN		0.
STATIC/TAXI	17.	
SUBSTANTIAL DAMAGE		5.
TOTAL DESTRUCTION		12.
MINOR/NONE/UNKNOWN		0.
UNKNOWN	3.	
SUBSTANTIAL DAMAGE		0.
TOTAL DESTRUCTION		3.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	16.	
RESULT	247.	

TABLE B-7

STATISTICS FOR ONE-ENGINE CRAFT

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	2354.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	249.	
TOTAL DESTRUCTION	2105.	
MINOR/NONE/UNKNOWN	0.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	38.	
NONSTATIC	2316.	
IFR		237.
VFR		2026.
BEL MIN/UNKNOWN/NOT REPORTED		53.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	472.	
SUBSTANTIAL DAMAGE		69.
TOTAL DESTRUCTION		403.
MINOR/NONE/UNKNOWN		0.
LANDING	415.	
SUBSTANTIAL DAMAGE		66.
TOTAL DESTRUCTION		349.
MINOR/NONE/UNKNOWN		0.
CRUISE	1412.	
SUBSTANTIAL DAMAGE		103.
TOTAL DESTRUCTION		1309.
MINOR/NONE/UNKNOWN		0.
STATIC/TAXI	34.	
SUBSTANTIAL DAMAGE		10.
TOTAL DESTRUCTION		24.
MINOR/NONE/UNKNOWN		0.
UNKNOWN	21.	
SUBSTANTIAL DAMAGE		1.
TOTAL DESTRUCTION		20.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	106.	
RESULT	2248.	

TABLE B-8

STATISTICS FOR OTHER THAN ONE-ENGINE CRAFT

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	704.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	110.	
TOTAL DESTRUCTION	575.	
MINOR/NONE/UNKNOWN	19.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	10.	
NONSTATIC	694.	
IFR		155.
VFR		501.
BEL MIN/UNKNOWN/NOT REPORTED		38.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	150.	
SUBSTANTIAL DAMAGE		21.
TOTAL DESTRUCTION		128.
MINOR/NONE/UNKNOWN		1.
LANDING	223.	
SUBSTANTIAL DAMAGE		34.
TOTAL DESTRUCTION		184.
MINOR/NONE/UNKNOWN		5.
CRUISE	305.	
SUBSTANTIAL DAMAGE		37.
TOTAL DESTRUCTION		256.
MINOR/NONE/UNKNOWN		12.
STATIC/TAXI	24.	
SUBSTANTIAL DAMAGE		18.
TOTAL DESTRUCTION		5.
MINOR/NONE/UNKNOWN		1.
UNKNOWN	2.	
SUBSTANTIAL DAMAGE		0.
TOTAL DESTRUCTION		2.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	85.	
RESULT	619.	

TABLE B-9

STATISTICS FOR RECIPROCATING ENGINE CRAFT

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	2912.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	331.	
TOTAL DESTRUCTION	2565.	
MINOR/NONE/UNKNOWN	16.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	44.	
NONSTATIC	2868.	
IFR		369.
VFR		2419.
BEL MIN/UNKNOWN/NOT REPORTED		80.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	594.	
SUBSTANTIAL DAMAGE		82.
TOTAL DESTRUCTION		511.
MINOR/NONE/UNKNOWN		1.
LANDING	591.	
SUBSTANTIAL DAMAGE		90.
TOTAL DESTRUCTION		497.
MINOR/NONE/UNKNOWN		4.
CRUISE	1653.	
SUBSTANTIAL DAMAGE		132.
TOTAL DESTRUCTION		1510.
MINOR/NONE/UNKNOWN		11.
STATIC/TAXI	52.	
SUBSTANTIAL DAMAGE		26.
TOTAL DESTRUCTION		26.
MINOR/NONE/UNKNOWN		0.
UNKNOWN	22.	
SUBSTANTIAL DAMAGE		1.
TOTAL DESTRUCTION		21.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	177.	
RESULT	2735.	

TABLE B-10

STATISTICS FOR NON-RECIPROCATING ENGINE CRAFT

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	146.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	28.	
TOTAL DESTRUCTION	115.	
MINOR/NONE/UNKNOWN	3.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	4.	
NONSTATIC	142.	
IFR		23.
VFR		108.
BEL MIN/UNKNOWN/NOT REPORTED		11.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	28.	
SUBSTANTIAL DAMAGE		8.
TOTAL DESTRUCTION		20.
MINOR/NONE/UNKNOWN		0.
LANDING	47.	
SUBSTANTIAL DAMAGE		10.
TOTAL DESTRUCTION		36.
MINOR/NONE/UNKNOWN		1.
CRUISE	64.	
SUBSTANTIAL DAMAGE		8.
TOTAL DESTRUCTION		55.
MINOR/NONE/UNKNOWN		1.
STATIC/TAXI	6.	
SUBSTANTIAL DAMAGE		2.
TOTAL DESTRUCTION		3.
MINOR/NONE/UNKNOWN		1.
UNKNOWN	1.	
SUBSTANTIAL DAMAGE		0.
TOTAL DESTRUCTION		1.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	14.	
RESULT	132.	

TABLE B-11

STATISTICS FOR THE PERIOD 1968-1970

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	1068.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	113.	
TOTAL DESTRUCTION	948.	
MINOR/NONE/UNKNOWN	7.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	20.	
NONSTATIC	1048.	
IFR		117.
VFR		913.
BEL MIN/UNKNOWN/NOT REPORTED		18.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	233.	
SUBSTANTIAL DAMAGE		31.
TOTAL DESTRUCTION		202.
MINOR/NONE/UNKNOWN		0.
LANDING	231.	
SUBSTANTIAL DAMAGE		37.
TOTAL DESTRUCTION		191.
MINOR/NONE/UNKNOWN		3.
CRUISE	574.	
SUBSTANTIAL DAMAGE		35.
TOTAL DESTRUCTION		535.
MINOR/NONE/UNKNOWN		4.
STATIC/TAXI	17.	
SUBSTANTIAL DAMAGE		10.
TOTAL DESTRUCTION		7.
MINOR/NONE/UNKNOWN		0.
UNKNOWN	13.	
SUBSTANTIAL DAMAGE		0.
TOTAL DESTRUCTION		13.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	61.	
RESULT	1007.	

TABLE B-12

STATISTICS FOR THE PERIOD 1971-1973

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	910.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	115.	
TOTAL DESTRUCTION	789.	
MINOR/NONE/UNKNOWN	6.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	11.	
NONSTATIC	899.	
IFR		119.
VFR		747.
BEL MIN/UNKNOWN/NOT REPORTED		33.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	178.	
SUBSTANTIAL DAMAGE		29.
TOTAL DESTRUCTION		148.
MINOR/NONE/UNKNOWN		1.
LANDING	192.	
SUBSTANTIAL DAMAGE		33.
TOTAL DESTRUCTION		158.
MINOR/NONE/UNKNOWN		1.
CRUISE	521.	
SUBSTANTIAL DAMAGE		45.
TOTAL DESTRUCTION		472.
MINOR/NONE/UNKNOWN		4.
STATIC/TAXI	13.	
SUBSTANTIAL DAMAGE		8.
TOTAL DESTRUCTION		5.
MINOR/NONE/UNKNOWN		0.
UNKNOWN	6.	
SUBSTANTIAL DAMAGE		0.
TOTAL DESTRUCTION		6.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	63.	
RESULT	847.	

TABLE B-13

STATISTICS FOR THE PERIOD 1974-1976

TOTAL PLANE ACCIDENTS OR INCIDENTS WITH FIRE INVOLVEMENT	1080.	
LEVEL OF DAMAGE		
SUBSTANTIAL DAMAGE	131.	
TOTAL DESTRUCTION	943.	
MINOR/NONE/UNKNOWN	6.	
PHASE OF OPERATION/WEATHER		
STATIC/UNKNOWN	17.	
NONSTATIC	1063.	
IFR		156.
VFR		867.
BEL MIN/UNKNOWN/NOT REPORTED		40.
PHASE OF OPERATION/LEVEL OF DAMAGE		
TAKEOFF	211.	
SUBSTANTIAL DAMAGE		30.
TOTAL DESTRUCTION		181.
MINOR/NONE/UNKNOWN		0.
LANDING	215.	
SUBSTANTIAL DAMAGE		30.
TOTAL DESTRUCTION		184.
MINOR/NONE/UNKNOWN		1.
CRUISE	622.	
SUBSTANTIAL DAMAGE		60.
TOTAL DESTRUCTION		558.
MINOR/NONE/UNKNOWN		4.
STATIC/TAXI	28.	
SUBSTANTIAL DAMAGE		10.
TOTAL DESTRUCTION		17.
MINOR/NONE/UNKNOWN		1.
UNKNOWN	4.	
SUBSTANTIAL DAMAGE		1.
TOTAL DESTRUCTION		3.
MINOR/NONE/UNKNOWN		0.
REASON FOR FIRE		
CAUSE	67.	
RESULT	1013.	

Table B6 - Statistics for Non-Fixed Wing Craft

Table B7 - Statistics for One-engine craft

Table B8 - Statistics for Other Than One-engine Craft

Table B9 - Statistics for Reciprocating Engine Craft

Table B10- Statistics for Non-reciprocating Craft

Table B11- Statistics for the Period 1968-1970

Table B12- Statistics for the Period 1971-1973

Table B13- Statistics for the Period 1974-1976

The first statistical tests examined differences in the statistics for the three 3-year periods in the data base. These included chi-squared tests for the following:

- Phase (Take-off, landing, or cruise) versus 3-year period
- Phase/weather versus 3-year period
- On or off airport versus 3-year period
- Distance from airport versus 3-year period.

There was no significance in any of these tests with one minor exception. For the phase and weather data, there was an increase during the nine-year period in below minimum or unknown accidents for weather. (This may be due to reporting practices.) The test based on data with a deletion of the unknown or below minimum category shows no significance in differences between the three 3-year periods.

Once the validity of the full nine year data base was established, the model was developed in a straightforward manner. For each class of aircraft an empirical probability was estimated giving the conditional probability that the accident took place either on or near the airport or during cruise. For each of these phases the conditional probability of substantial damage or total destruction was estimated. One class of aircraft with unusual characteristics was non-fixed wing or non-powered craft. These craft showed a different statistics from fixed wing powered craft and in addition will be utilizing different amounts of carbon fibers in 1973. Most of these aircraft are, of course, helicopters.

In examining the statistics for non-reciprocating engine planes and planes with more than one engine, some differences from one-engine reciprocating craft were noted. There was a higher percentage of on-airport accidents and a higher percentage of substantial damage accidents for these craft. Both of these classes of aircraft represent larger planes than single engine reciprocating engine craft and are logical candidates for consolidation in any classification scheme. In fact, there are no significant differences in phase of operation or in damage probabilities conditional on phase between the two classifications. Although there is a great deal of overlap among the two classes, that is, most non-reciprocating engine craft are also aircraft that have more than one engine, the similarity of statistics shows a certain pattern for larger general aviation aircraft. Because of this the final breakdown of aircraft was established as follows:

- Non-Fixed wing or non-powered craft
- Single reciprocating engine aircraft
- Multiple or non-reciprocating engine aircraft

The statistics for these classes are presented in Table A14. The conditional probabilities of aircraft type, cruise, on airport and damage were based on this table. As noted, the major differences between the statistics of the larger aircraft and the smaller single reciprocating engine craft are the larger percentages of on airport accidents and substantial damage accidents. To some extent, these differences are correlated. That is, larger general aviation aircraft have higher percentages of substantial damage accidents because on aircraft (or near airport) accidents have higher percentages of substantial damage accidents. In fact, the conditional damage probabilities given the major phase category (on or near airport versus cruise) were very similar.

B.4 GENERAL AVIATION ACCIDENT RATES AND FINAL MODEL

Table B15 presents accident rates and total aircraft hours and miles flown for the period 1969-1978. It is noted that the number of fatal and total accidents has remained approximately constant since about 1972 while total activity has increased. The model, however, does not require a per-mile, per-hour, or per-operation accident rate. Total number of expected accidents per year can be allocated to the various counties according to some measure of activity. Thus, despite the decrease in accident rate that has been observed over the past several years, the number of accidents has not substantially varied, and we assumed that the expected number of general aviation fire accidents is 3,058 divided by 9, or 340 accidents per year. 25% (corresponding to the percent of fleet that carry CF) or 85 would involve CF aircraft.

It should be noted that the same manufacturers who produce general aviation aircraft also produce the aircraft that are utilized by air taxi and commuter carriers. We did not perform a separate study of air taxi commuter accidents as they do not represent a significant number of operations. In 1978, for example, the number of operations for each aircraft carrier category at F.A.A. control tower airports were:

Air Carrier	10,063,259
Air Taxi	3,773,484
G/A	50,798,779
Military	2,537,912
Total	67,173,434

The 1990 forecast, however, from the Wharton long-term industry and economic forecasting model[1] predicts 8.4 million air taxi and commuter operations. In order to develop an estimate for the impact of air taxi and commuter operations on the national risk profile, we adjusted upward the 340 accident per year to account for air taxi and commuter operations. This adjustment factor was estimated to be .02 which is consistent with the total estimated air taxi and commuter operations and general aviation operations in 1993 of 12.5 and 293.5 million, respectively. Thus the total number of estimated general aviation and air taxi and commuter fire accidents was 354 per year of which 88 would involve aircraft carrying CF. This procedure, of course, assumes that the accident rate for air taxi and commuter operations is the same as for general aviation operations and that the resulting geographic distribution and release statistics are similar.

In developing the final conditional probabilities of damage and type, the figures in Table B14 were adjusted to account for different growth rates of the different classes of aircraft. As noted in Table 2-1, which was used in project future fleet sizes, the annual growth rates have been 6.3%, 4.8%, and 8.6% for multi-engine craft, single-engine craft and rotor craft, respectively. We would expect relative accident frequencies for the three categories in Table B14 to grow at approximately the same rate. (Thus, for example, the relative share of helicopter accidents should increase.) The table of final conditional probabilities reflects these growth rates using 1973 as the base year for the Table B14 data.

[1]FAA Aviation Forecast, Fiscal years 1979 to 1990 U.S. Department of Transportation, page 35.

TABLE B-14

STATISTICS FOR FINAL CLASSIFICATIONS

GENERAL AVIATION FIRES (1968-1976)

	Cruise				On or Near Airport			
	Substantial	Total Destruction	Unknown	Cruise Total	Substantial	Total Destruction	Unknown	Airport Total
Non-Fixed Wing or Non-Powered	22	125	0	147	24	74	0	98
Single Reciprocating Engine	81	1182	0	1263	121	720	0	841
Multiple or Jet Engine	37	258	12	307	74	321	7	402
Total	140	1565	12	1717	219	1115	7	1341

The final part of the model requires allocation of the total number of accidents to the various counties in the United States. A separate allocation procedure was developed for cruise and on or near airport accidents. For on or near airport accidents it was assumed that the probability that an accident takes place in any given county is proportional to the number of general aviation operations in that county. For the 905 airports which now have FAA control towers or are candidates for control towers we obtained the number of operations for general aviation as well as air taxi and commuter for the year 1977, and we obtained forecasts for the years 1978 through 1990.[2] We then used the forecast to determine a growth rate to predict the operations at these airports in 1993. These airports in 1977 included an estimated 30% of all general aviation operations and 100% of all air taxi and commuter operations.

The remainder of general aviation operations for 1993 was derived from estimates of general aviation operations by state for 1987.[3] Again an annual growth rate was used to estimate state operations for 1993. From the total operations of the 905 airports and the total state operations we determined for each state how many general aviation operations will not originate or terminate at one of the 905 airports. These unallocated operations were allocated to the countries within the state according to population. They were then added to the totals for the 905 airports by county to estimate the total operations by county.

While accidents that take place on or near an airport are generally related to the number of operations at the airport, accident rates for cruise accidents, on the other hand, might be more appropriately determined by the total number of miles or hours. An estimate of total hours

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2 Terminal Area Forecast Fiscal Years 1970 to 1990, U.S. Department of Transportation, Federal Aviation Administration, 1978.

3 General Aviation Forecast 1975 to 1987 State, Regional and National Operations, prepared for the U.S. DOT FAA Office of Aviation Policy, Final Report, April, 1976.

or miles by county is thus needed to allocate cruise accidents to the various counties. We were not, however, able to obtain any data on general aviation mileage wtihin each county. By the same type of procedures noted above, we were able to obtain forecasts of local and itinerant operations for each county in the country. The time per operation of itinerant and local flights are 38 and 11 minutes, respectively. (Specifically, for example, each itinerant operation takes on average 76 minutes and consists on average of 5.4 operations.) We then assumed that the air mileage of each itinerant and local operation is approximately the same as all other operations of the same type, and that each operation takes place completely within the one or two counties where the take offs and landings occur. These assumptions are obviously not true. They are conservative, however, in the sense that aircraft mileage will be assigned wholely to the originating and terminating counties where the density of vulnerable facilities is generally greater than any other county of the operations path. By making these assumptions the probability that a given cruise accident takes place within a given county is proportional to 38 times the number of itinerant operations plus eleven times the number of local operations.

Thus, in summary the general aviation accident model is as follows:

1. There are 48 cruise accidents and 37 on or near airport fire accidents per year (plus an additional estimated 2 and 1 for air taxi and commuter) or a total of 88.

2. For each cruise accident

   $$\text{Prob(County i)} = \frac{38\ \text{Itin}_i + 11\ \text{Loc}_i}{\Sigma_i\ 38\ \text{Itin}_i + 11\ \text{Loc}_i}$$

   where

   Itin_i = Estimated itinerant operations for county i

   Loc_i = Estimated local operations for county i

   and for each on or near airport accident

   $$\text{Prob(county i)} = \frac{\text{Itin}_i + \text{Loc}_i}{\Sigma \text{Intin}_i + \text{Loc}_i}$$

3. The conditional probabilities of phase and aircraft type, based on Table B-14 and adjusted for growth rates, are as presented in Table 3-1.

TABLE B-15

ACCIDENTS, FATALITIES, RATES U.S. GENERAL AVIATION

1969-1978

Year	Accidents Total	Accidents Fatal	Fatalities	Aircraft-Hours Flown (000) c/	Aircraft-Miles Flown (000) c/	Accident Rates Per 100,000 Aircraft-Hours Flown Total	Accident Rates Per 100,000 Aircraft-Hours Flown Fatal	Accident Rates Per Million Aircraft-Miles Flown Total	Accident Rates Per Million Aircraft-Miles Flown Fatal
1969	4,767	647	1,495 b/	25,351	3,926,461	18.8	2.55	1.21	0.164
1970	4,712 a/	641 a/	1,310	26,030	3,207,127 d/	18.1	2.46	1.47	0.200
1971	4,648	661	1,355	25,512	3,143,181	18.2	2.59	1.48	0.211
1972	4,256 a/	695 a/	1,426 b/	26,974	3,317,100	15.8	2.57	1.28	0.209
1973	4,255 a/	723 a/	1,412	29,974 r/	3,728,500	14.2 r/	2.41 r/	1.14	0.193
1974	4,425 a/	729 a/	1,438	31,413 r/	4,042,700	14.1 r/	2.31 r/	1.04	0.180
1975	4,237 a/	675 a/	1,345	32,024 r/	4,238,400	13.2 r/	2.10 r	1.00	0.159
1976	4,193 a/	695 a/	1,320	33,922 r/	4,476,014	12.3 r/	2.04 r/	0.94	0.155
1977	4,286 a/	702 a/	1,436	35,792 r/	4,786,400	12.0 r/	1.96 r/	0.90	0.147
1978 P	4,609	795	1,690 b/	36,600	4,519,900	12.6	2.17	1.02	0.176

a/ Suicide/sabotage accidents included in all computations except rates (1970-1, 1972-3, 1973-2, 1974-2, 1975-2, 1976-4, 1977-1).

b/ Includes air carrier fatalities (1969-82, 1972-5, 1978-142) when in collision with general aviation aircraft.

c/ Source: FAA

d/ Beginning in 1970, the decrease in aircraft-miles flown is the result of a change in the FAA standard for estimating miles flown.

r/ Revised

NATIONAL TRANSPORTATION SAFETY BOARD
Washington, D.C. 20594
January 3, 1979

APPENDIX C

EQUIPMENT DATA

Facility Category	Equipment Category Number	Equipment	$\bar{E}$	Number of Pieces Factor	Number of Pieces Index **	$ Cost Per Piece
Households	1	TV/Stereo White Goods Furnace	3.4E+09	5.0E+00	04	80
Police	2	Motor Generator	1.0E+06	1.0E+00	01	98
	3	Radio Trans. in Veh.	2.0E+08	8.5E-04	03	250
	4	Teletype Mach. Misc. Eqpt.	2.4E+08	1.9E-05	03	108
	5	Small Computer Line Printer Small Computers Large Computer	1.1E+09	1.1E-05	03	4489
	6	PBX (Small)	1.8E+09	2.2E-05	03	9800
	7	CRT Terminals Radio Control Console	2.4E+09	7.4E-05	03	113
Fire	8	Motor Generator (large)	1.5E+06	1.0E+00	01	9
	9	Motor Generator (small)	1.5E+07	2.0E+00	01	20
	10	PBX (small)	7.3E+07	1.0E+00	01	1040
	11	Radio Trans. in veh.	2.0E+08	3.1E-04	03	80
	12	Radio Control Console	5.0E+08	7.8E-06	03	80
	13	Radio Trans-ceivers	9.0E+08	4.7E-06	03	250
Post Office Sorting Center	14	Sorter with OCR Sorter w/o OCR	2.5E+08	2.2E-05*	03	800

*Truncate
**Indices in Appendix D

Facility Category	Equipment Category Number	Equipment	$\bar{E}$	Number of Pieces Factor	Number of Pieces Index	$ Cost Per Piece
Subway	15	Auto. Fare Coll.	3.3E+07	1.0E-02	07	250
	16	Radio	2.5E+08	0.5E+00	07	80
	17	Sch. Syst.- Sm. Comp.	2.8E+08	5.0E-03	07	800
		PBX (small)				
R.R. Terminal	18	Mobile Trans.	3.9E+08	2.0E+01	20	80
	19	PBX (small)	5.4E+08	1.0E+00	20	800
	20	CRT Terminals	7.9E+09	1.8E+01	20	137
		Radio Control Console				
		Transceivers				
General Manufacturing*	21	Var. Freq. Cont.	1.0E+09	1.0E-02	09	15,200
	22	Digital Speed Control	2.0E+09	3.3E-03	09	1,700
	23	Transf. Sub. Switch	6.3E+09	2.7E-03	09	65,300
	24	Fork Lift Trucks	1.7E+07	3.3E-02	09	30
		Battery Charger-Truck				
	25	Programmable Palletizer	1.7E+08	1.7E-03	09	250
	26	Inj. Mold Heater Controls	3.3E+08	4.0E-02	09	80
	27	Quality Control Instr.	3.3E+09	3.3E-02	09	250
		Computer Facility (small)	3.3E+09	2.0E+00	08	300
		PBX (small)				

*Equipment categories 21-22 from SIC 2824; 23 from SIC 3714; 24-28 from SIC 2844

Facility Category	Equipment Category Number	Equipment	$\bar{E}$	Number of Pieces Factor	Number of Pieces Index	$ Cost Per Piece
Manufacturer of Electronic Equipment	29	In process spray paint	1.3E+07	5.9E-04	13, 15 17, 11	3,760
	30	In process plaster parts	2.0E+07	5.9E-04	13, 15, 17, 11	2,420
	31	Master Oscillator Controller	1.4E+08	2.4E-03	13, 15, 17, 11	8,838
		Incomping Insp. Test Eqpt.				
	32	Assembly Line Signal Inter.	2.5E+08	4.1E+00	13, 15, 17, 11	1.16
		In process elect. comp.				
		In process burn-in				
	33	Inj. mold temp & pressure	5.0E+08	1.2E-02	13, 15, 17, 11	1,800
	34	In process life test	3.3E+09	5.9E-02	13, 15 17, 11	2.50
Telephone Co.	35	Switching Center	1.4E+09	1.0E+00	04	0.065

Facility Category	Equipment Category Number	Equipment	$\bar{E}$	Number of Pieces Factor	Number of Pieces Index	$ Cost Per Piece
Radio/TV	36	Mobile Mini Cam	1.9E+07	3.0E+00	22, 24	2,500
	37	Studio Eqpt. Transf. & Transm Control Room PBX (small)	4.0E+08	4.0E+00	22, 24	1,225
General Merchandise Retailers	38	Motor generator (large)	1.8E+06	2.0E-03	27, 31 33, 35	8
	39	PBX (small)	7.7E+08	1.0E+00	26, 30 32, 34	800
	40	POS Terminals	2.5E+09	2.0E-01	27, 31 33, 35	250
	41	HVAC Controls	7.7E+09	4.0E-03	27, 31 33, 35	30
Retail Grocers	42	POS Terminals HVAC Controls	1.0E+09	1.4E+01	28	226
Finance & Insurance	43	PBX (small)	3.3E+09	1.0E+00	36, 38 40, 42	800
Computer Services	44	PBX (small)	2.8E+08	1.0E+00	44	800
	45	Gen. Office Eqpt.	2.8E+09	1.0E+00	45	30
	46	Computer (large)	2.9E+09	1.0E+00	44	8,500
Electronic R&D, Univ.	47	PBX (small)	3.3E+09	1.0E+00	46, 50	800
	48	Instruments	3.3E+09	1.0E+00	47, 51	30
Hospitals	49	Generator (large)	5.0E+06	1.0E+00	48	300
	50	Gen. Instr. Patient Area	1.5E+08	1.8E-01	05	250
	51	PBX	3.0E+09	1.0E+00	48	800
	52	X-Ray	6.0E+09	5.5E-03	05	800

Facility Category	Equipment Category Number	Equipment	$\bar{E}$	Number of Pieces Factor	Number of Pieces Index	$ Cost Per Piece
Airports	53	TTY at Terminal	2.0E+09	4.1E-04	06	250
	54	ASR	2.0E+09	*		2500
	55	Computer at Tower	3.1E+09	*		800
	56	Consoles at Tower	3.1E+09	4.7E-05	06	250
Auto & Truck Assembly	57	Spray Paint Drying Tunnel	5.7E+04	2.5E-04	19	12080
	58	Spot Welder Controls	3.3E+06	1.3E-02	19	1700
	59	Prog. Auto. Welders	9.8E+07	5.0E-04	19	12800
	60	Assembly Line Controllers	9.8E+07	5.0E-04	19	12800
	61	Welder Controls	1.0E+03	5.0E-04	19	1900
	62	PBX (small)	1.0E+09	1.0E+00	18	800
	63	Computer System (large)	1.0E+09	1.0E+00	18	12800

*Set to 1 if category 06 $\geq$ 1,000

APPENDIX D

DEMOGRAPHIC DATA INDICES

Index	Demographic Data Category
1	Dummy Variable = 1 Per County
2	Area
3	Population
4	Families
5	Hospital Beds
6	Air Carrier Operations
7	Number of Subway Cars
8-9	Facilities, Employees SIC Code 1900
10-11	Facilities, Employees SIC Code 3573
12-13	Facilities, Employees SIC Code 3650
14-15	Facilities, Employees SIC Code 3660
16-17	Facilities, Employees SIC Code 3670
18-19	Facilities, Employees SIC Code 3710
20-21	Facilities, Employees SIC Code 4011
22-23	Facilities, Employees SIC Code 4830
24-25	Facilities, Employees SIC Code 4890
26-27	Facilities, Employees SIC Code 5310
28-29	Facilities, Employees SIC Code 5410
30-31	Facilities, Employees SIC Code 5600
32-33	Facilities, Employees SIC Code 5700
34-35	Facilities, Employees SIC Code 5900
36-37	Facilities, Employees SIC Code 6020
38-39	Facilities, Employees SIC Code 6100
40-41	Facilities, Employees SIC Code 6200
42-43	Facilities, Employees SIC Code 6300
44-45	Facilities, Employees SIC Code 7370
46-47	Facilities, Employees SIC Code 7391
48-49	Facilities, Employees SIC Code 8060
50-51	Facilities, Employees SIC Code 8220

APPENDIX E

DETAILS ON VARIANCE OF DOLLAR LOSS PER ACCIDENT

To determine the dollar loss statistics given an accident, it is necessary to condition the calculation on the number of failures. Thus we have the following conditional expectation formulae for the first and second moments of dollar loss L given and accident. In the two summations, the variable ℓ represents the number of failures and $p(\ell)$ represents the probability of ℓ failures.

$$EL = \sum_{\ell=1}^{\infty} p(\ell)\ E(L|\ell)$$

and

$$EL^2 = \sum_{\ell=1}^{\infty} p(\ell)\ E(L^2|\ell)$$

and

$$\mathrm{VAR}\ L = EL^2 - E(L)^2$$

where

$E(x|\ell)$ represents the expected value of variable X given ℓ failures

Because expectations are additive, we have

$$E(L|\ell) = \ell E(X_0|\ell)$$

and

$$EL = \sum_{\ell=1}^{\infty} \ell p(\ell)\ E(X_o|\ell)$$

$$= EX_o\ EN$$

where X_o represents the dollar loss per failure and N is the number of failures per accident.

For the variance computation, by considering the individual scenario probabilities, one can derive the following expression:

$$EL^2 = \sum_{\ell=1}^{\infty} p(\ell) \sum_{i,k} P_i\ Q_k\ (\ \ell Var\ (X_o|i,\ k)) \quad + \ell^2 E\ (X_o|i,k)^2$$

where now

k = Amount released

i = County

ℓ = Number of failures

P_i and Q_k are the scenario probabilities (See Appendix A) and the statistics of X_0 given i and k are based on the failure rates for each equipment class and scenario. An alternate expression for EL^2 can be obtained by considering the covariance of two separate losses given ℓ failures. The expression that can be derived in this case is

$$EL^2 = \sum_{\ell=1}^{\infty} p(\ell)\ (\ell \text{ Var } (X_0|\ell) + \ell^2\ E(X_0|\ell)^2 + \ell(\ell - 1) \text{ cov}_\ell)$$

where

cov_ℓ = covariance of two separate losses given ℓ failures

The approximate expression given in Chapter 5 (i.e., expression 5-1) follows from the above if one assumes that cov_ℓ is zero and that the distribution of $(X_0|\ell)$ in independent of ℓ, the number of failures. These assumptions are important only if $\ell > 1$. Since the probability of multiple failures is very low, the approximate expression in Chapter 5 is virtually identical to the exact expression for Var L.

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16. Abstract

A Poisson type model was developed and exercised to estimate the risk of economic losses through 1993 due to potential electric effects of carbon fibers released from United States general aviation aircraft in the aftermath of a fire. Of the expected 354 annual general aviation aircraft accidents with fire projected for 1993, approximately 88 could involve carbon fibers. The average annual loss was estimated to be about $250 (1977 dollars) and the likelihood of exceeding $107,000 (1977 dollars) in annual loss in any one year was estimated to be at most one in ten thousand.

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